THE DEVELOPMENT AND EVALUATION OF A REVERSE FLOW MICROFILTER

Report to the Water Research Commission

BY

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EXECUTIVE SUMMARY

Background

In conventional woven fibre microfiltration (WFMF), a suspension is pumped into a flexible porous tube, or array of tubes, fabricated from woven polyester. Clear liquid permeates the porous wall and is recovered as the permeate, while contaminants are retained within the tube. This technology was developed in South Africa, and is currently exploited in three processes - the EXXFLOW Process (Epoc patent), the horizontal tubular filter press (WRC patent) and the vertical tubular filter press (WRC patent).

Internationally, there has been a progressive swing towards immersed membrane microfiltration (IMM), particularly in membrane bioreactors and in some potable water production applications. In IMM, the membranes are submerged in the feed suspension, and permeate is sucked through the membrane walls leaving the contaminants in the feed suspension. In general, the power requirements for IMM systems may be significantly less that that required for crossflow systems.

This project concerns a proposal for a new IMM technology that utilises flexible woven fibre tubes - the woven fibre reverse-flow microfilter (RFMF). Here, a tubular porous support is inserted into each woven fibre tube. The tubes are manifolded at both the top and the bottom, and one of the manifolds is connected to a suction pump. Now, permeate may be sucked through the membrane walls from the outside to the inside. Thus the inexpensive WFMF curtain may be used as an IMM.

Objectives and Approach

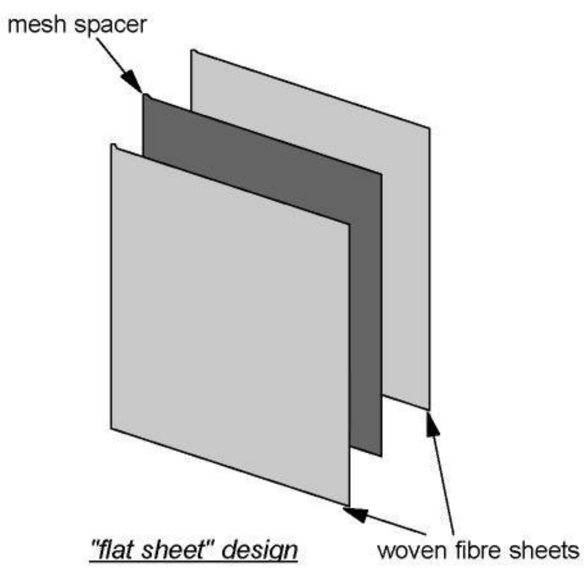
This is a preliminary project to assess the technical viability and potential of the RFMF system, and hence whether the new technology should be developed further. Three criteria were chosen to indicate the technical viability - separation efficiency, productivity, and ease of cleaning.

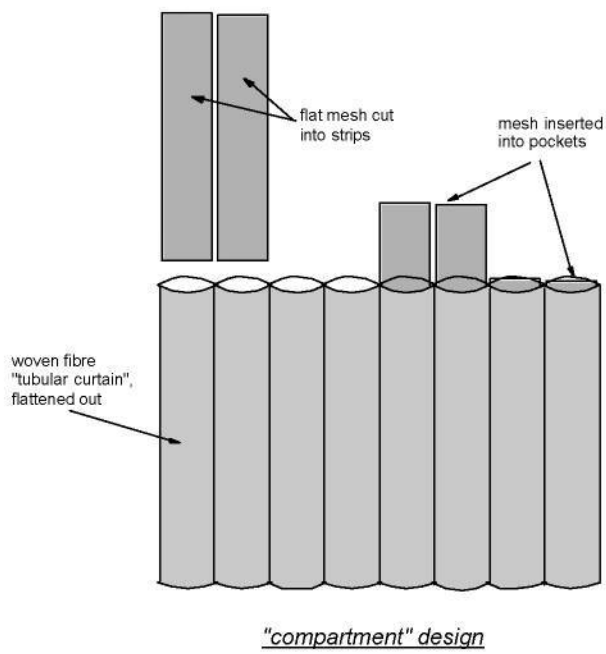
Investigations were performed on a laboratory scale immersed membrane rig on four suspensions, viz. limestone, raw river water, a bentonite/kaolin mixture and a biological sludge from an aerobic reactor. Separation efficiency was determined by measurement of the feed and permeate turbidities. Productivity was assessed by monitoring the permeate flux and operating pressure profiles, at both sub-critical and supercritical fluxes. The effectiveness of cleaning was determined by comparing the trans-membrane differential pressure (DP) profiles, at a specified permeate flux, before and after cleaning.

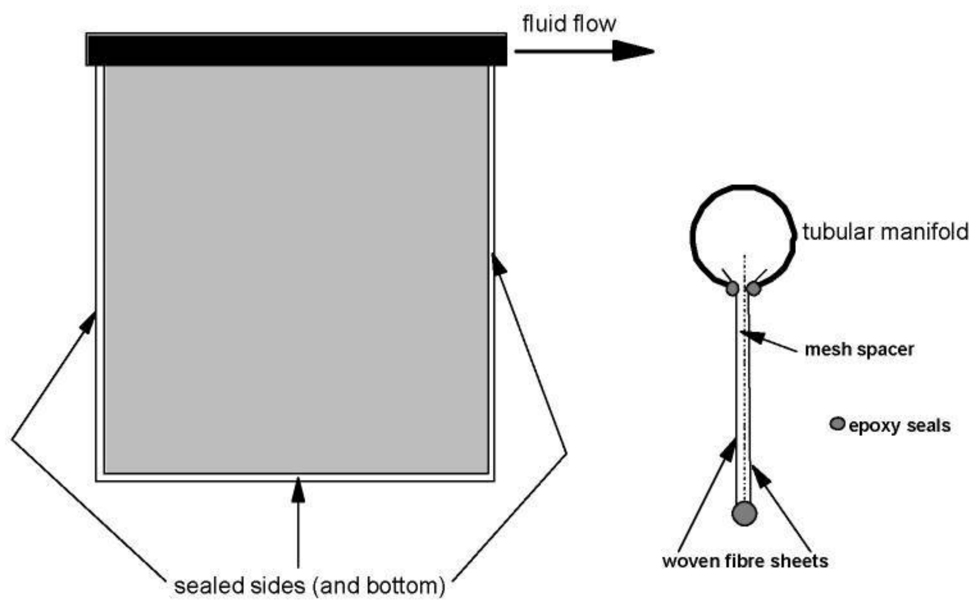
All investigations were performed in a constant flux mode, i.e. the permeate flux was maintained at a set value, and the DP increased with time as the membrane fouled. Further fouling reduction strategies such as air scouring and operation at low sub-critical fluxes were deliberately avoided, so as to assess the true potential of the system under adverse operating conditions.

Change in Mechanical Design

The RFMF, as initially conceived, consisted of tubular supports inserted into a conventional WFMF curtain. During the course of 2001, two variations on this geometry were conceived. Firstly, the tubular porous supports could be replaced with a flat mesh. Sheets of flat mesh would be inserted into each "tube" in a curtain. This would then be manifolded at the top and/or the bottom, and operated as a conventional flat sheet immersed membrane. Secondly, the woven fibre curtain could be replaced with woven fibre flat sheets. These would then be separated by a sheet of flat mesh and manifolded. This approach is the same as that used in existing flat sheet immersed membranes (e.g. Kubota), with the difference that woven fibre fabric is used instead of a flat sheet membrane. These new designs would have major advantages over the initial tubular system, including ease of fabrication, reduced fabrication costs, greater packing density, reduced membrane costs, and possibly improved separation. In view of all the above, the project team decided to suspend further investigations on the tubular design, and focus investigations on the flat sheet designs. For clarity, the version fabricated from two flat sheets would be referred to as the *flat sheet design* (FSD), and the version fabricated from the woven fibre curtain will be referred to as the *compartment design* (CD).







manifolding of modules

Results

The RFMF system gave permeate turbidities that could be regarded as very good to excellent. The permeate turbidities on limestone range from 0.2 NTU to 1 NTU, for a feed turbidity exceeding 999 NTU. On raw river water, a product turbidity of approximately 1 NTU is obtained for a feed of approximately 30 NTU. The product from the bentonite/kaolin trials also ranges from 0.2 NTU to 1 NTU, for a feed turbidity of around 750 NTU. For the biological sludge at high fluxes, the permeate turbidity ranges from 0.6 NTU to 1 NTU, while the product from the lower flux runs ranges from 0.8 NTU to 2 NTU. In general, the product turbidities over the range of suspensions tested is < 1 NTU, with the exceptions noted on the low flux biological sludge.

Runs on limestone were performed at fluxes of 170 LMH and 340 LMH, corresponding to stable DPs of 10 kPa and 20 kPa respectively. In runs on raw river water, fluxes were maintained at 150 LMH, and the corresponding DPs increased from about 40 kPa to around 80 kPa over three hours. "High flux" runs on a bioreactor sludge were performed at approximately 45 LMH, and the DPs increased from 10 kPa to around 60 kPa over 6 hours. Bentonite/kaolin experiments were performed at 35 LMH, resulting in DPs increasing by about 25 kPa in 2 hours. "Low flux" runs on a biological sludge at fluxes ranging from 7 LMH to 15 LMH yielded no DP increases over 3,5 hours.

Mechanical cleaning was extremely effective in removing the fouling layer on the RFMF and wholly restoring the permeability of the membranes. This has been confirmed for the whole range of suspensions studies, i.e. limestone, raw river water, bentonite/kaolin and activated sludge. In no instance did irreversible fouling occur necessitating a chemical clean. It has also been shown that highly fouled membranes may be restored by allowing them to dry out. Here the fouling layer also dries out and can thereafter be easily removed mechanically.

Backflushing was not particularly successful on the flat sheet module, but was very effective on the compartment module. Backflushing reduced the DP, and hence extended the effective filtration period before the membrane needs to be cleaned. Further, the rate of DP increase after each backflush is similar to that before the backflush, confirming that the fouling layer has indeed been reduced. Backflushing is not currently practiced on commercial flat sheet IMM systems, and could be a potential advantage of the compartment RFMF module design.

The RFMF system gives the same performance at sub-critical fluxes as the current commercial IMM systems, i.e. operation at a stable DP that does not increase with time. This indicates that the RFMF system could also be designed and configured to run in the sub-critical flux mode, should economic or operational factors necessitate this.

Discussion

These results indicate clearly that the criteria for technically viability have been adequately met. In addition, it is perceived that the technology would have various advantages over current commercial IMM systems. These include :-

(i) no chemical cleaning – In this project, and previous projects on WFMF, chemical cleaning was never required.

(ii) ability to be backflushed – the current commercial flat sheet IMM system does not employ backflushing for fouling reduction. In this project it has been clearly shown that backflushing is very effective in reducing fouling in the compartment model. This will enable the RFMF compartment model to operate at high fluxes, with periodic backflushing to reduce fouling.

(iii) extremely robust membranes – if a membrane is mechanically damaged and develops a hole, it can be easily patched. This cannot be done with any of the current commercial IMM membranes.

(iv) operation over a wide range of feeds – previous investigations on WFMF have shown that the polyster fabric is very resistant to chemicals, and can operate at temperatures up to about 70 ^{0}C. It has been operated on feeds ranging from concentrated acids to concentrated bases, including operation on hydrofluoric acid.

(v) Local development and production – the fabric was developed locally and is produced by a local textile company. Modules can be wholly produced locally.

(vi) Potentially inexpensive – whilst a detailed costing of modules has not been done, it is expected that the local modules would be less expensive than imported ones, particularly because of point (v) above.

All the above point to the conclusion that the RFMF technology could be an excellent IMM system for niche applications in developing economies, as an alternative to the current IMM technologies being marketed internationally. Potential applications for the technology include :

(i) pretreatment of high turbidity raw waters in rural/peri urban areas to remove suspended material and colloids prior to polishing and disinfection by other membranes/UV radiation/chlorine etc. There are currently no membrane technologies that are addressing this very important application in developing economies.

(ii) treatment of raw waters using gravity as the driving force. This would be particularly applicable in remote areas where no electricity is available, as well as for disaster relief (e.g. floods)

(iii) small scale membrane bioreactors for treatment of effluents at source

(iv) industrial solid-liquid separation systems

Conclusion

All the above point to the conclusion that the RFMF technology could be an excellent IMM system for niche applications in developing economies, as an alternative to the current IMM technologies being marketed internationally. Accordingly, it is proposed that this very promising technology should be developed further.

ACKNOWLEDGEMENTS

The Project Team gratefully acknowledges the invaluable input of the following people :

(i) Professor C Visvanathan, of the Asian Institute of Technology, for initiating the idea of using the woven fibre microfilter as an immersed membrane filter

(ii) Mr G Lok, of ESKOM, for initiating the idea of using the woven fibre microfilter in a flat sheet configuration

(iii) The Project Steering Committee for its excellent guidance during the project

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1 INTRODUCTION

1.1 Background to the project

In conventional woven fibre microfiltration (WFMF), a suspension is pumped into a flexible porous tube, or array of tubes, fabricated from woven polyester (Figure 1). Clear liquid permeates the porous wall and is recovered as the permeate, while contaminants are retained within the tube. These contaminants accumulate to form a fouling layer, or cake, on the inside of the tube wall. Periodically, the tubes are cleaned, removing the cake and restoring the permeability of the tubes. One method of achieving this is to alternately depressurise the tube and pulse fluid through it. Other methods of cleaning include brushes, rollers and high-pressure sprays.

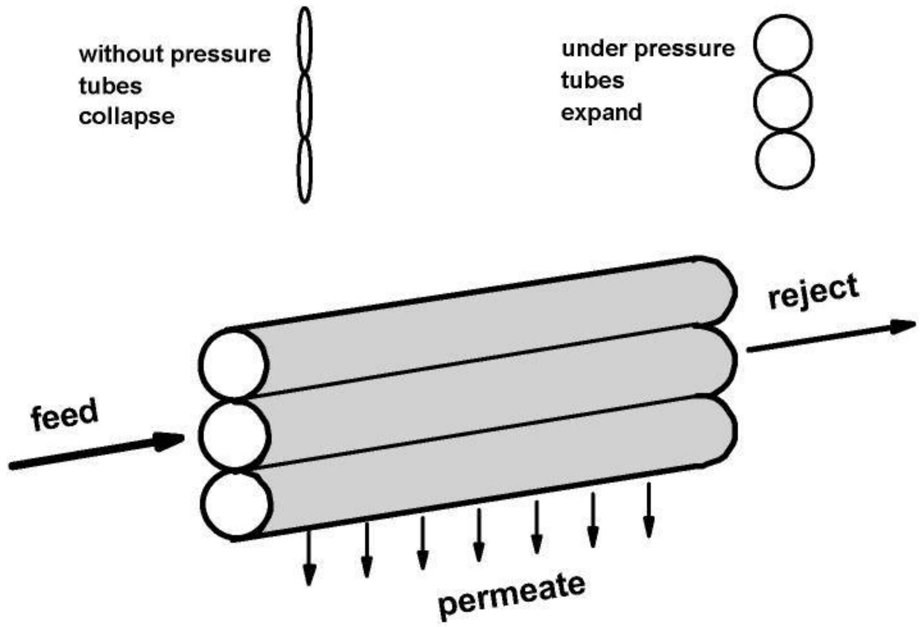

Figure 1 : Crossflow Woven Fibre Microfiltration

The above technology is currently exploited in three processes - the EXXFLOW Process (Epoc patent), the horizontal tubular filter press (WRC patent) and the vertical tubular filter press (WRC patent). WFMF technology was developed in South Africa, and offers various advantages over conventional rigid microfiltration membranes, especially in terms of microfiltration applications in developing economies.

Internationally, there has been a progressive swing towards immersed membrane microfiltration (IMM), particularly in membrane bioreactors and in some potable water production applications. In IMM, the membranes are submerged in the feed suspension (Figure 2).

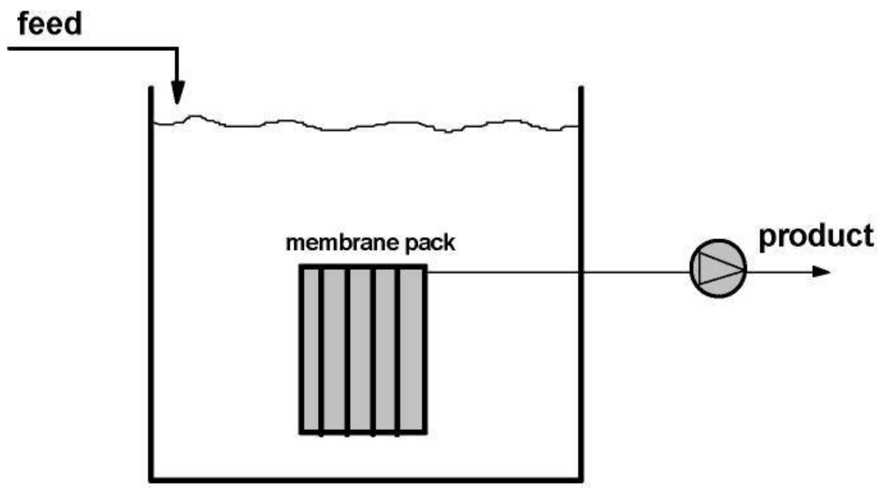

Figure 2 : Immersed Membrane Filtration

Permeate is sucked through the membrane walls leaving the contaminants in the feed suspension. Hence in IMM, permeate flow occurs from the outside of the membrane into the membrane, in contrast to conventional membranes where permeate flow occurs from the inside to the outside (Figure 3). In general, the power requirements for IMM systems may be significantly less that that required for crossflow systems.

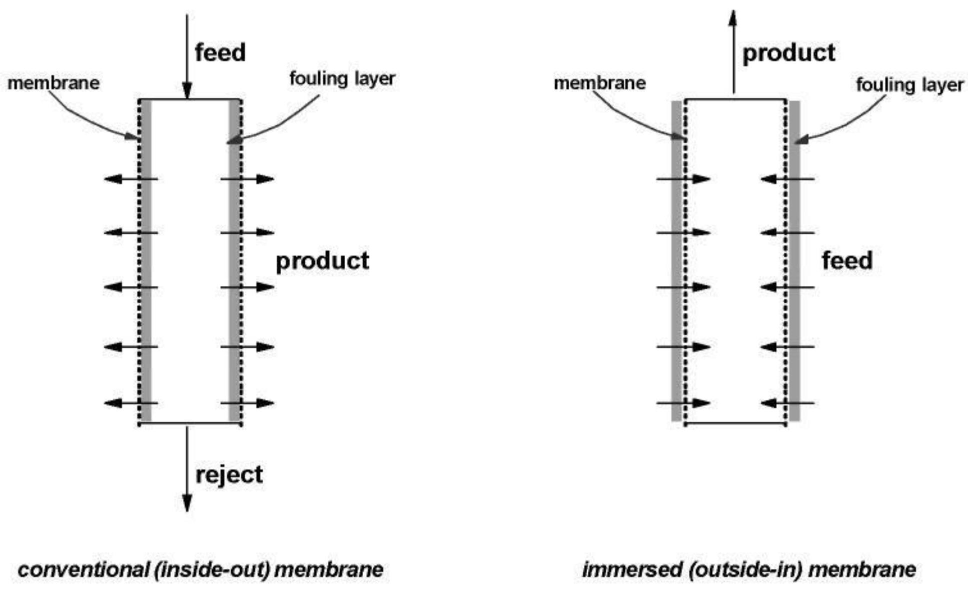

Figure 3 : Fluid flow in crossflow and immersed membranes

Following an idea proposed by Dr Visvanathan, of the Asian Institute of Technology, a completely new IMM technology that utilises flexible woven fibre tubes was proposed - the reverse-flow woven fibre microfilter (RFMF). Here, a porous support is inserted into each woven fibre tube. In its simplest form, the porous support consists of a PVC pipe with numerous holes drilled along its length, and whose diameter is slightly smaller than the inside diameter of the flexible tubes. The tubes are manifolded at both the top and the bottom, and one of the manifolds is connected to a suction pump (Figure 4).

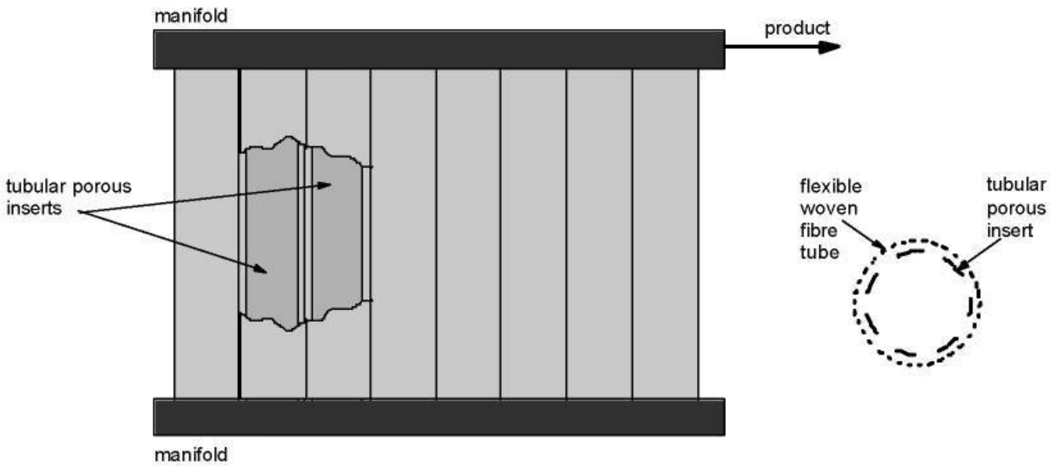

Figure 4 : Proposed RFMF module

The filter is completely submerged in a vessel containing the suspension to be filtered. Using the suction pump, liquid is sucked through the tube wall, i.e. flow occurs from the outside to the inside of the tube. Now, the fouling layer forms on the outside of the tube wall. Periodically, the flow is reversed, i.e. from the inside to the outside (backwashing). This destabilises and removes the fouling layer, restoring the flux. The backwash may assisted by introducing bubbles of air into the inside of the tubes during the backwash.

If fouling becomes significant, and is not removed by backwashing, the tubes are simply allowed to dry out. It has been shown that in WFMF dried foulants are very easily removed from the tube wall, either by vibration or by backwashing. Hence, in most applications, this system will never require a chemical clean.

Possible applications include the following : pretreatment of water from a pond/river/dam, for potable/industrial use; industrial solid-liquid separation / pretreatment of industrial effluents; immersed membrane bioreactors.

Potential advantages over competing IMM and crossflow technologies include the following :

- all the advantages of WFMF - inexpensive, robust, cannot be irreversibly fouled.
- dead-end operation, requires less energy than cross-flow operation. Do not need to pump feed from pond/dam to plant, since membranes can be immersed into pond/dam - lower pumping and piping costs.
- No chemical cleaning required - simply take unit offline and allow curtains to dry.
- tubes are flexible - hence no fracture/rupture (this has proved to be a problem when rigid tubes have been used in immersed membrane bioreactors).

The concept could potentially lead to a new woven fibre IMM technology that would be relatively inexpensive and very applicable in developing economies. This is a preliminary project to determine the technical feasibility of the concept.

1.2 Objectives

(i) To evaluate the technically viability of the reverse flow woven fibre microfilter (RFMF) on a single tube system.

(ii) To investigate the upscaling of the system to a full curtain.

(iii) To evaluate the performance of a single curtain over an extended period, to determine the robustness and reliability of the technology.

(iv) To produce a preliminary costing of the technology.

(v) To identify potential niche applications for the technology.

2 APPROACH

The overall objective of this project is to determine the technical viability and the potential of the RFMF system, and hence determine whether the technology should be developed further. Three criteria were chosen to indicate the technical viability :

(i) separation efficiency :- The question here is whether the RFMF system can give an acceptable product quality. This will be determined by measurement of the feed and permeate turbidities.

(ii) productivity :- This relates to the relationship between permeate flux and operating conditions. The issues to be addressed are :- can the membrane give an acceptable permeate flux at low operating pressures; are there operating strategies that can improve productivity; is the productivity consistent and repeatable. This will be determined by monitoring the permeate flux and operating pressure profiles.

(iii) ease of cleaning :- Can fouled membranes be easily restored, preferably without the use of chemical cleaners. This will be determined by comparing the trans-membrane differential pressure (DP) profiles, at a specified permeate flux, before and after cleaning. If the cleaning is unsuccessful, the DP profile would not change significantly. If the cleaning is successful, the DP would be expected to decrease to a value close to that of the original unfouled membrane, and the subsequent rate of rise in DP would be similar to that obtained before the clean.

3 HYDRODYNAMIC ASPECTS OF IMMERSED MEMBRANES

3.1 Operating Modes

In immersed membrane systems, permeate flows through the walls of the membrane from the outside to the inside. This permeate flow causes contaminants to accumulate at the outer wall of the membrane, forming a fouling layer which increases the hydrodynamic resistance to permeate flow. This increased resistance manifests either as an increase in the differential pressure across the membrane (TMP), or as a decrease in the permeate flux.

There are two extreme operating modes for immersed systems :- *constant pressure* operation or *constant flux* operation.

In constant pressure operation, the differential pressure across the membrane is maintained at a steady value. Consequently the permeate flux decreases as the resistance of the fouling layer increases with time. When the permeate flux reaches an unacceptably low value, the membrane has to be cleaned to remove the fouling layer and restore the permeate flux (Figure 5).

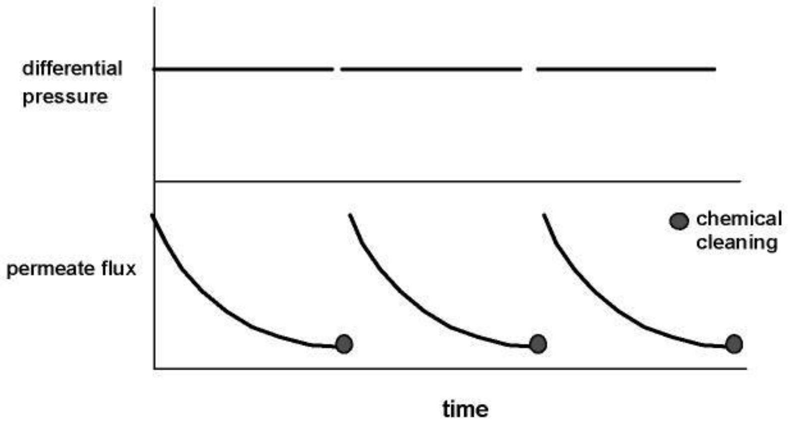

Figure 5 : Constant pressure operation

In the constant flux mode, the permeate flux is maintained at a steady value. Here, the TMP across the membrane increases with time, as the resistance of the fouling layer increases (Figure 6). When the TMP reaches a high value, the membrane has to be cleaned to remove the fouling layer and restore a lower TMP. One physical limitation to the TMP is the vapour pressure of the feed liquid. If the TMP approached the vapour pressure, the liquid will boil.

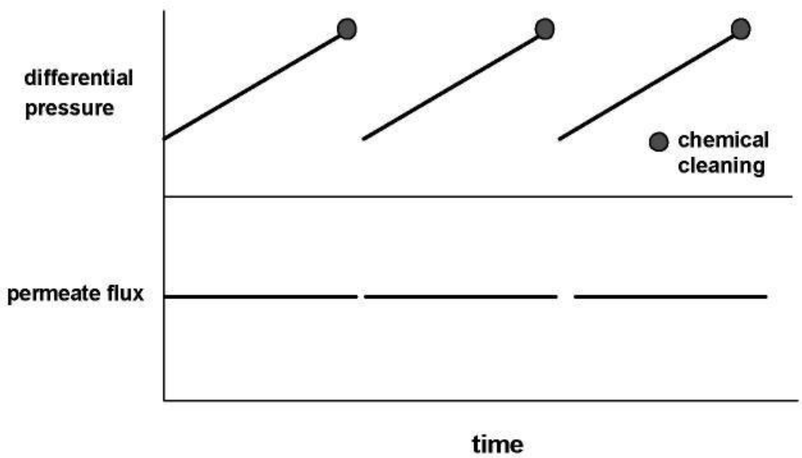

Figure 6 : Constant flux operation

3.2 Strategies to reduce fouling

3.2.1 Air scouring

Clearly, the operating time before cleaning could be extended if the rate of fouling could be controlled and reduced. A common method of reducing the rate of fouling is to use air bubbles to scour the outer wall of the membrane. This approach is employed in two of the current market leaders in IMM systems, viz Zenon and Kubota. Air diffusers are placed strategically below the immersed membranes. Coarse air bubbles form at the diffusers and rise through the membrane pack, scouring the surface of the membranes and reducing the fouling layer. The membrane packs and diffusers are designed so as to maximize the scouring effect, and designs are generally patented. The Memcor system uses a combination of air scouring and backflushing to reduce the fouling layer.

The efficiency of air scouring is a function of the bubble size, bubble rise velocity, interaction with the membrane surface etc, all of which are very strictly dependant on scale. Hence, in practice, any air scouring strategy cannot be determined on a laboratory scale and extrapolated to larger scales. Development of the strategy must occur on a "slice" of a full-scale reactor.

3.2.2 Operation below the critical flux

In systems that employ air scouring, the rate of removal of foulants away from the fouling layer is a complex function of the aeration rate, size of bubbles, membrane pack design etc. The rate of deposition of foulants onto the membrane is directly related to the permeate flux. At high permeate fluxes, the rate of deposition of foulants exceeds the rate at which they are scoured away, and the fouling later will grow with time. Operating at a lower permeate flux will cause the fouling layer to grow at a slower rate. At some lower permeate flux, the rate of deposition of foulants will be equaled by the rate of their removal. Now, there will be no net deposition of foulants, and the fouling layer will cease growing and will remain constant with time. Theoretically, therefore, the system could operate continuously at this point, without any increase in TMP or decrease in permeate flux. The permeate flux at which this occurs is termed the critical flux, J_{crit} (Figure 7).

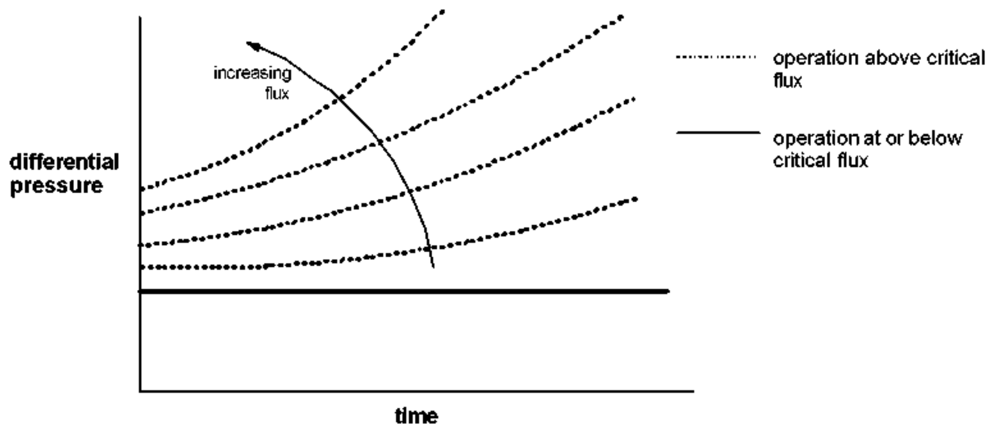

Figure 7 : Differential pressure profiles as a function of flux

The current commercial immersed membrane systems all attempt to operate below the critical flux, so as to maximize the operating time between membrane cleans. This requires a greater membrane area and a significant energy input for aeration. However, this apparently offsets the cost of more frequent cleans. Further, operating at a low flux requires a low trans-membrane pressure. Current commercial systems exploit the gravitational head of the feed suspension above the membrane pack to provide this TMP, thus reducing the pumping requirements of the system.

In conventional (i.e. not immersed) membrane systems the fouling characteristics of the system, i.e. the inter-relationship between crossflow velocity, operating pressure and permeate flux, may be determined from laboratory experiments on a single membrane tube and reasonably extrapolated to larger scale systems. However, the fouling characteristics of immersed membrane systems cannot be extrapolated from laboratory experiments to larger scales. As noted above, the scouring mechanism in immersed systems is a complex function of aeration rate, size of bubbles, hydrodynamics in the membrane pack etc, which are all strong functions of scale. Hence it has been generally found that to determine the critical flux characteristics of any given immersed system, experiments must be conducted on a "slice" of the full-scale configuration, and cannot be determined from experiments performed on scaled down apparatus.

3.2.3 Backflushing

Backflushing is commonly used in inside-out capillary and hollow fibre membrane systems, and applies equally well to outside-in (immersed) membrane systems. In backflushing, the direction of permeate flow is periodically reversed. This causes foulants to detach from the fouling layer and be swept out into the reject stream. In general, backflushing cannot remove all foulants. There will still exist some residual fouling, which will build up with time eventually necessitating a chemical clean. Effectively, backflushing serves to increase the time between chemical cleans (constant pressure and constant flux operation), and can also increase the permeate production (constant pressure operation only) (Figure 8).

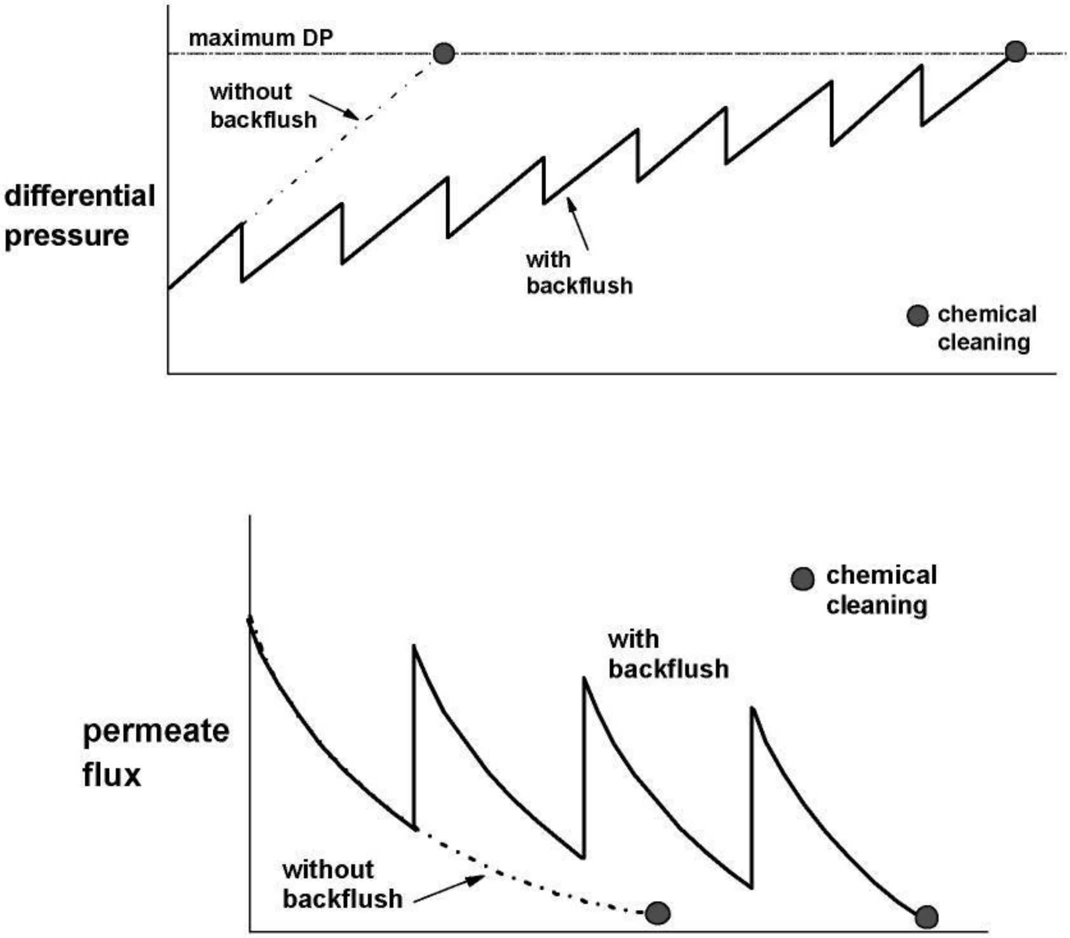

Figure 8 : Effect of backflushing

As noted above, the Memcor system, which employs capillary membranes, uses a combination of backflushing and air scouring to reduce fouling. The Zenon system, which also uses capillary membranes, can also be backflushed. The Kubota system employs flat sheet membranes and does not use backflushing. The reasons for this are not known to this project, but could be due to the difficulties with obtaining an even flow distribution across a flat sheet during backflushing, as well as the difficulties associated with pumping backflush liquid through the porous support structure in the Kubota membranes.

3.3 Approach taken in this project

The first choice concerns the operating mode to be adopted, i.e., constant flux or constant pressure. In immersed systems that use only the head of liquid above the membrane pack as the driving force, implementation of constant pressure operation is fairly easy. However, in systems that use a pump to remove permeate, operating at a constant pressure is substantially more complex, requiring an automated control valve and/or a pump with speed control. In pumped systems, it is significantly easier to operate at a constant flux. This can be implemented by installing a restricting valve on the permeate line, or by an appropriate choice of pump. Further, operating at a constant flux is also easier from a control point of view. It is cheaper to base control decisions (backflushing, cleaning etc) on measurements of the differential pressure than on measurements of the flux. Accordingly, it was decided that investigations would be performed at constant fluxes, and the differential pressure across the membrane would be used as the control variable.

The next choice concerns whether investigations should be performed under optimal anti-fouling hydrodynamic conditions, i.e. with effective air scouring, operation below critical flux and optimal backwashing. The following points were considered :

(i) Since the objective of this project is to evaluate the *potential* of the new technology, it was felt that the performance should be determined under poor or worst case hydrodynamic conditions, rather than optimal conditions.

(ii) As noted above, optimized hydrodynamic conditions cannot be easily translated from laboratory scale to full-scale. If the technology's potential is proven in this project under poor hydrodynamic conditions, the further development of the technology would be warranted. Then, optimization of performance can occur when the technology is being developed to a larger scale.

(iii) Part of the objective of this project is to determine whether the membrane can recover from fouling, i.e. whether they can be easily cleaned. This would require many investigations on highly fouled membranes, which cannot be obtained under optimal hydrodynamic conditions.

Accordingly it was decided that investigations should be conducted under highly fouling conditions, i.e. with no/minimal scouring and at supercritical fluxes. However, some investigations would be performed with backflushing and at low fluxes, to indicate the membranes potential performance under optimal hydrodynamic conditions.

4 CHANGE IN MODULE DESIGN

At the Inaugural Steering Committee Meeting (2001), the Steering Committee recommended that investigations should focus on determining the performance and limitations of a single tube, rather than investigations on curtains. The identification of the parameters that limit the performance of single tubes would then lead to more effective upscaling of the system.

With this in mind, the work programme was modified to the following :

(i) Investigate and test different internal porous supports. This would include different types of supports as well as supports of different diameters.

(ii) Preliminary performance trials on a range of different suspensions, and hence identifying a suspension on which further detailed investigations would be performed. The main performance criterion for these preliminary trials would be separation ability, as measured by turbidity.

(iii) Investigations into the geometric limitations on a single tube.

However, during the course of 2001, there was a significant development in the project which changed the fundamental basis of the proposed technology. The RFMF, as initially conceived, consisted of tubular supports inserted into a conventional WFMF curtain. During the course of 2001, two variations on this geometry were conceived following a meeting with Dr E P Jacobs (US) and Mr G Lok (ESKOM). These were :

(i) *Compartment design* - Replacing the tubular porous support with flat mesh. Sheets of flat mesh would be inserted into each "tube" in a curtain (Figure 9). This would then be manifolded at the top and/or the bottom, and operated as a conventional flat sheet immersed membrane (Figure 11)

(ii) *Flat sheet design* - Replacing the woven fibre curtain with woven fibre flat sheets. These would then be separated by a sheet of flat mesh (Figure 10). Similar to the compartment design, this would then be manifolded at the top and/or the bottom, and operated as a conventional flat sheet immersed membrane (Figure 11). This approach is the same as that used in existing flat sheet immersed membranes (e.g. Kubota), with the difference that woven fibre fabric is used instead of a flat sheet membrane.

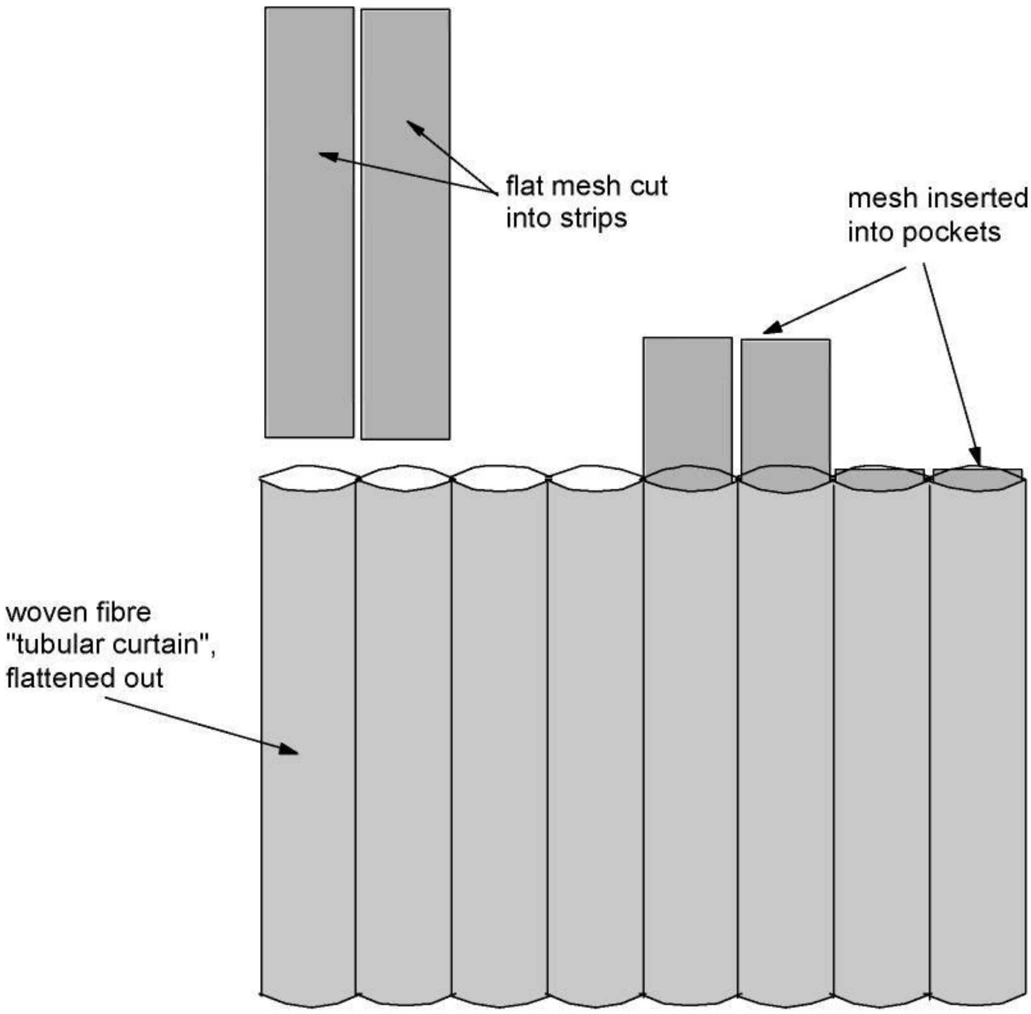

Figure 9 : Compartment design

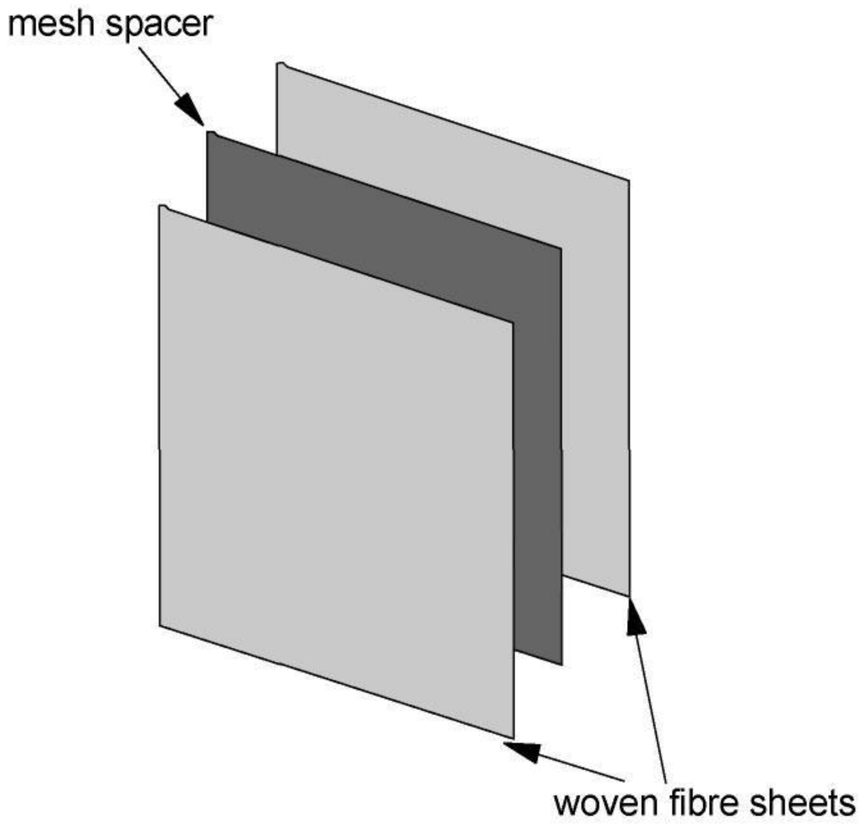

Figure 10 : Flat sheet design

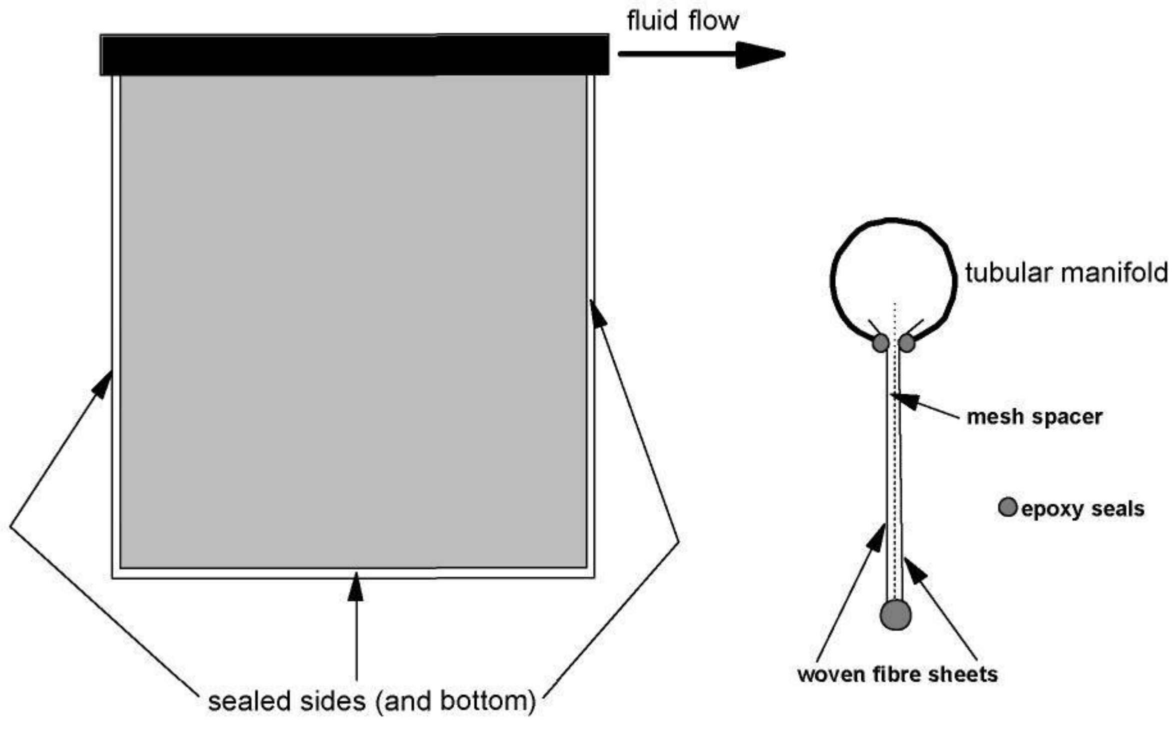

Figure 11 : Manifolding of both compartment and flat sheet designs

The new systems described above would have major advantages over the initial tubular system. These include :

(i) ease of fabrication. The flat sheet configuration would be significantly easier to fabricate than the tubular geometry. The manifold for the flat sheet systems could consist simply of a 16 mm or 20 mm tube.

(ii) reduced fabrication costs. It is estimated that the flat sheet configuration would cost less than 20 % of the cost of the tubular system.

(iii) greater packing density. The endblock and manifold in the tubular system is at least 50 mm wide, while the manifold in the flat sheet system would be a maximum of 20 mm. This would enable a far greater packing density for the flat sheet systems.

(iv) Reduced membrane costs. The tubular configuration uses the specialist woven fibre curtain. The second flat sheet configuration can use any flat sheet material, including flat sheet filtration fabric that is currently being produced on a large scale for mining operations.

(v) Improved separation. In discussions with the supplier of the woven fibre curtain, it emerged that the "tightness" of the curtain was limited by the fact that the fibres had to be woven into a tubular array. Accordingly, it was not possible to produce a tighter curtain to improve separation. However, flat sheet fabric was available that had a tighter weave. Hence, the new flat sheet designs could have a better performance than the tubular curtain.

In view of all the above, the project team decided to suspend further investigations on the tubular design, and focus investigations on the flat sheet designs. For clarity, the version fabricated from two flat sheets would be referred to as the *flat sheet design* (FSD), and the version fabricated from the woven fibre curtain will be referred to as the *compartment design* (CD).

5 EXPERIMENTAL

5.1 Test Suspensions

It was decided that investigations should be conducted on a mineral suspension, raw river water and a biological suspension, to broadly cover the possible applications of the technology.

The mineral suspension consisted of limestone (KULU 5, nominal particle size of 5 microns) suspended in water, to a concentration of 5 g/L. The feed turbidity of this suspension exceeded the range of the turbidity meter used (999 NTU).

In investigations during 2001 and 2002, raw water with a turbidity of around 30 NTU was obtained from the head of the Wiggens Water Works and used in investigations. However, during 2002 the turbidity at Wiggens dropped to below 10 NTU, often having a value of around 3 NTU. A survey of other water sources around Durban also yielded feed turbidities of around 5 NTU. This was regarded as too low for investigations, especially since the woven fibre system requires a fouling layer to form to effect its best separation. It was then decided to represent raw river water with a bentonite/kaolin suspension. Whilst this mixed suspension does not by any means replicate the complex fouling potential of raw river water, it has previously been used as a test suspension by investigators as it has both particulate and gel-like fouling characteristics. The bentonite/kaolin suspension used in this investigation had a solids concentration of 1 g/L, with bentonite and kaolin in the ration 1,5:1.

The biological suspension used was activated sludge obtained from a laboratory-scale aerobic reactor set up in the Water Technology Group's laboratory at M L Sultan Technikon. The reactor was initially seeded with sludge obtained from a waste water treatment works, and was subsequently fed on a synthetic feed. The biomass concentration for investigations reported here ranged from 3 g/L to 5,6 g/L.

5.2 Apparatus

A schematic diagram of the experimental apparatus is shown in Figure 10, and photographs of the reactor and a typical module are shown in Figure 11. The reactor consisted of a square Perspex tank of dimensions 500 mm x 500 mm x 500 mm. The test modules consisted of either flat sheets or a section cut from a woven fibre curtain, with approximate filtration area dimensions of 23 cm x 20 cm. The hydrostatic head of the liquid above the module was not significant.

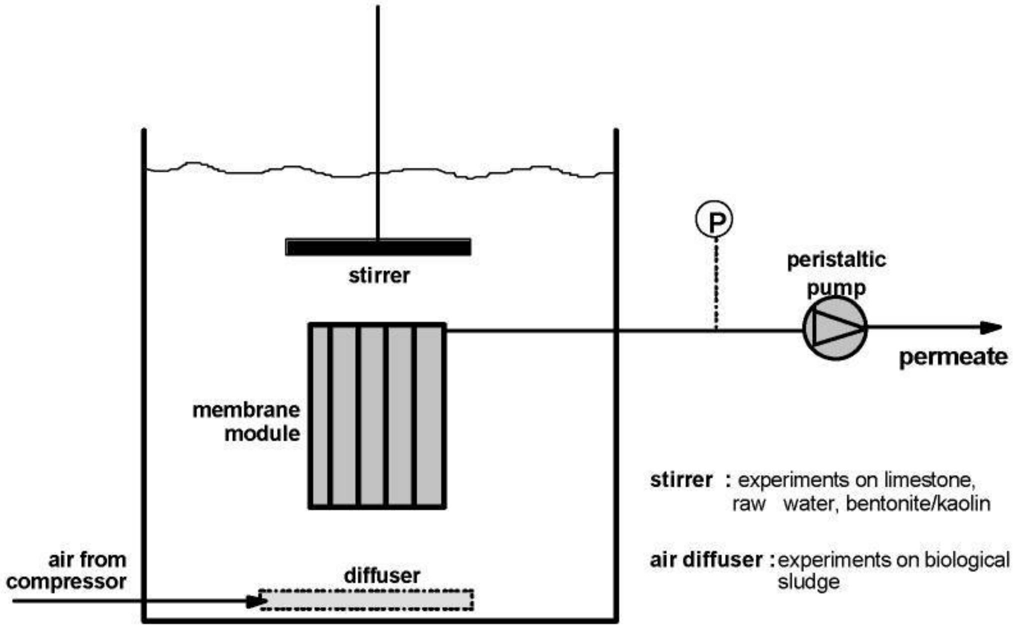

Figure 12 : Schematic of experimental rig

Figure 13 : Module and rig setup

In the investigations involving limestone and bentonite/kaolin, a stirrer was used to maintain a uniform suspension. However, the stirrer speed was set to the minimum to limit scouring effects on the membrane. In the experiments on the biological sludge, aeration was used to maintain a uniform suspension. However, the aeration rate was kept to a minimum, well below that used in commercial immersed membrane bioreactors, in order to limit scouring effects.

6 RESULTS AND DISCUSSION

During this project it was found that various modules developed leaks, due to the epoxy not penetrating the woven fabric effectively (see Recommendations). Those runs have been excluded from this report.

6.1 Separation Efficiency

These investigations were performed at high fluxes, without any significant scouring. The speed of the peristaltic pump was set to the appropriate value to give the desired flux. The feed and permeate turbidities and trans-membrane differential pressure were monitored with time. When the DP reached a high value (usually around 60 kPa to 80 kPa) the run was stopped and the membranes were cleaned mechanically.

The feed and permeate turbidities obtained on the limestone suspension, raw river water, bentonite/kaolin suspension, biological suspension (high fluxes) and biological suspension (low fluxes) are shown in Figures 12 to 16.

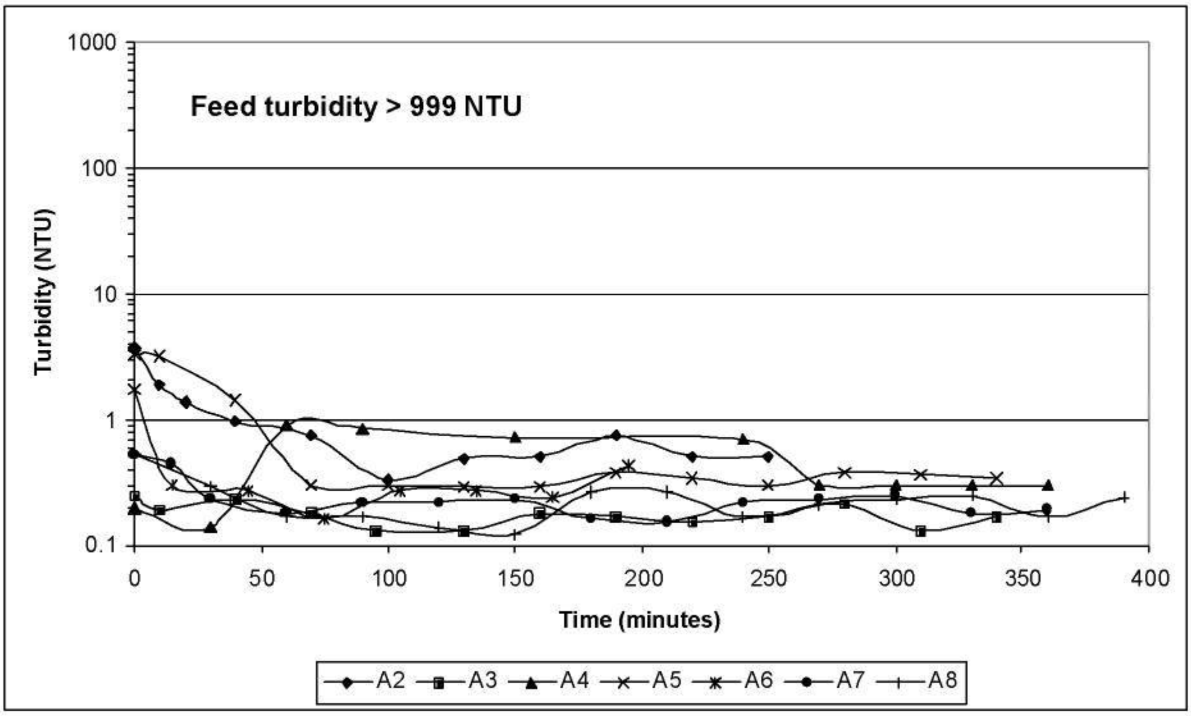

Figure 14 : Turbidities obtained on limestone suspension (170 LMH and 340 LMH)

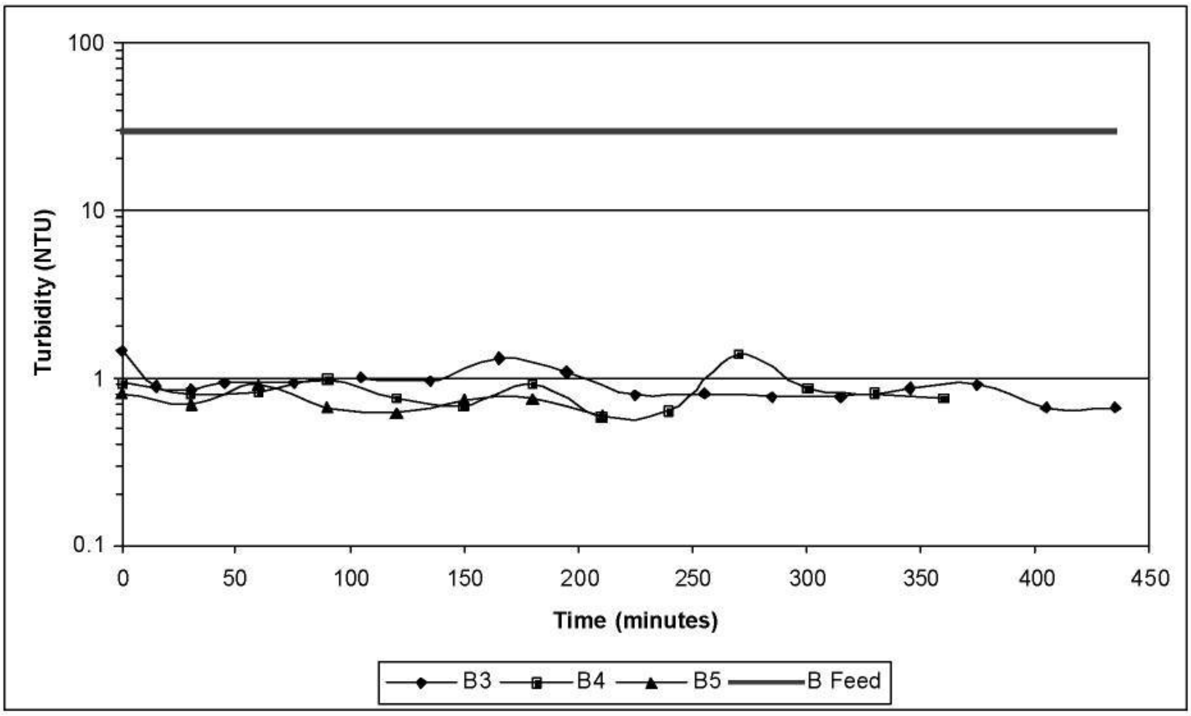

Figure 15 : Turbidities obtained on raw river water (150 LMH)

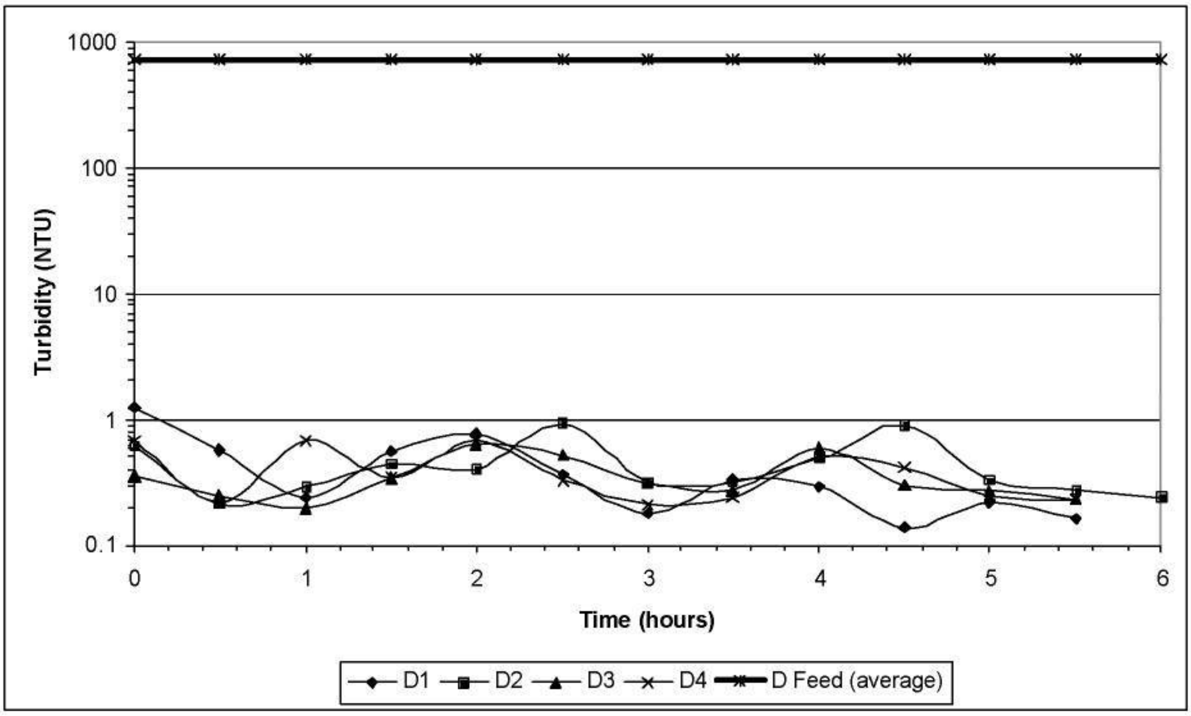

Figure 16 : Turbidities obtained on bentonite/kaolin suspension (~ 35 LMH)

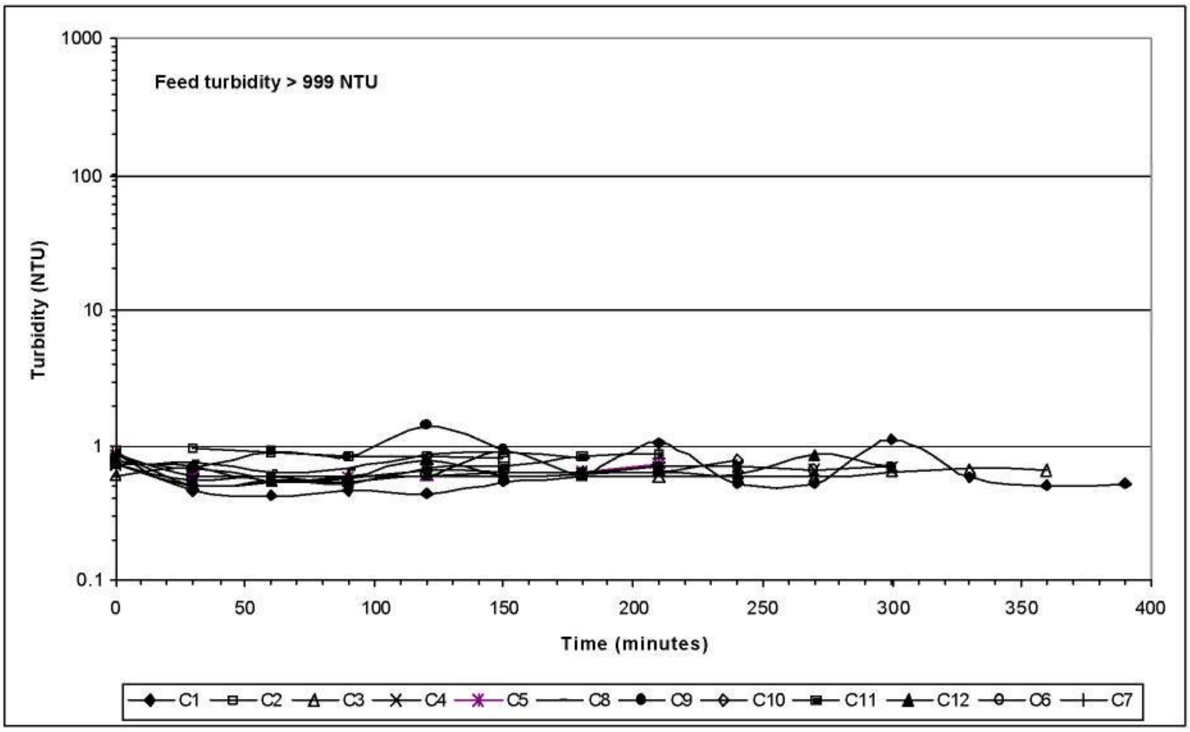

Figure 17 : Turbidities obtained on biological suspension at high fluxes (50 LMH)

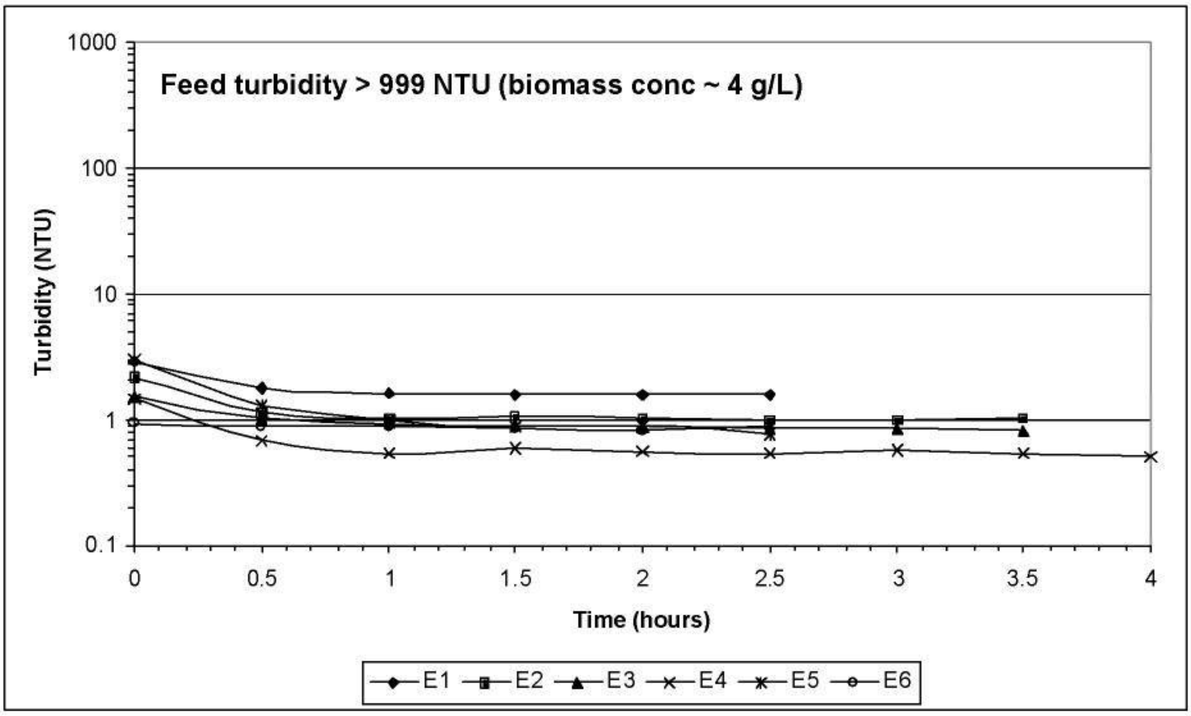

Figure 18 : Turbidities obtained on a biological suspension at low fluxes (< 15 LMH)

The permeate turbidities on limestone range from 0.2 NTU to 1 NTU, for a feed turbidity exceeding 999 NTU. On raw river water, a product turbidity of approximately 1 NTU is obtained for a feed of approximately 30 NTU. The product from the bentonite/kaolin trials also ranges from 0.2 NTU to 1 NTU, for a feed turbidity of around 750 NTU. For the biological sludge at high fluxes, the permeate turbidity ranges from 0.6 NTU to 1 NTU, while the product from the lower flux runs ranges from 0.8 NTU to 2 NTU. In general, the product turbidities over the range of suspensions tested is < 1 NTU, with the exceptions noted on the low flux biological sludge.

[Note that the high and low flux runs on the biological sludge were conducted on different batches of sludge at differing sludge ages etc. Hence, it cannot be concluded that operating at the higher flux gives a better product turbidity.]

The current commercial IMM systems all claim product turbidities of < 1 NTU, and in general between 0.2 NTU and 0.5 NTU. In another Water Technology Group project, investigations conducted on a Kubota flat sheet membrane on a biological sludge gave a permeate turbidity of 0.3 NTU to 0.5 NTU.

The proposed applications for the RFMF technology include pretreatment of industrial effluents, industrial solid-liquid separations, pretreatment of high turbidity raw river waters, water treatment in remote regions, and possibly immersed membrane bioreactors. For these applications, the separations efficiencies obtained above may be regarded as very good to excellent.

6.2 Fouling and Cleaning

In most real applications, a membrane will eventually become fouled. Operational strategies such as scouring, sub-critical flux operation, backflushing etc reduce the *rate* of fouling, but will not prevent the eventual fouling of the membrane. The ability to be cleaned and recover permeability after being fouled is a critical aspect of the technical viability of any membrane technology.

It is usually possible to find a concoction of chemicals that will remove any given fouling layer. However, if chemical cleaning can be avoided the applicability, economics and environmental impact of the technology will improve greatly. It will also make the technology more sustainable in developing economies, where regular access to chemical cleaners may not be guaranteed.

In previous investigations into WFMF, a major advantage was that the system never required a chemical clean. Mechanical agitation (e.g. pulsing) or drying was sufficient to remove the fouling layer. This is probably because the WFMF system does not have "pores" that can be penetrated by foulants as in a conventional rigid membrane. Accordingly, mechanical agitation and drying were tested as cleaning strategies in this project.

6.2.1 Mechanical agitation

Constant flux were performed at high fluxes to accelerate fouling. The trans-membrane DP was monitored. When this reached a high value of around 60 kPa to 80 kPa, the run was stopped and the surface of the membranes were scrubbed with a brush, while still wet. A new run was then started at the set flux.

The permeate flux and DP profiles for limestone are shown in Fig 17 and 18. With the exception of run A4, the starting DPs and the rate of increase in DP are similar, indicating the effectiveness of the mechanical cleaning.

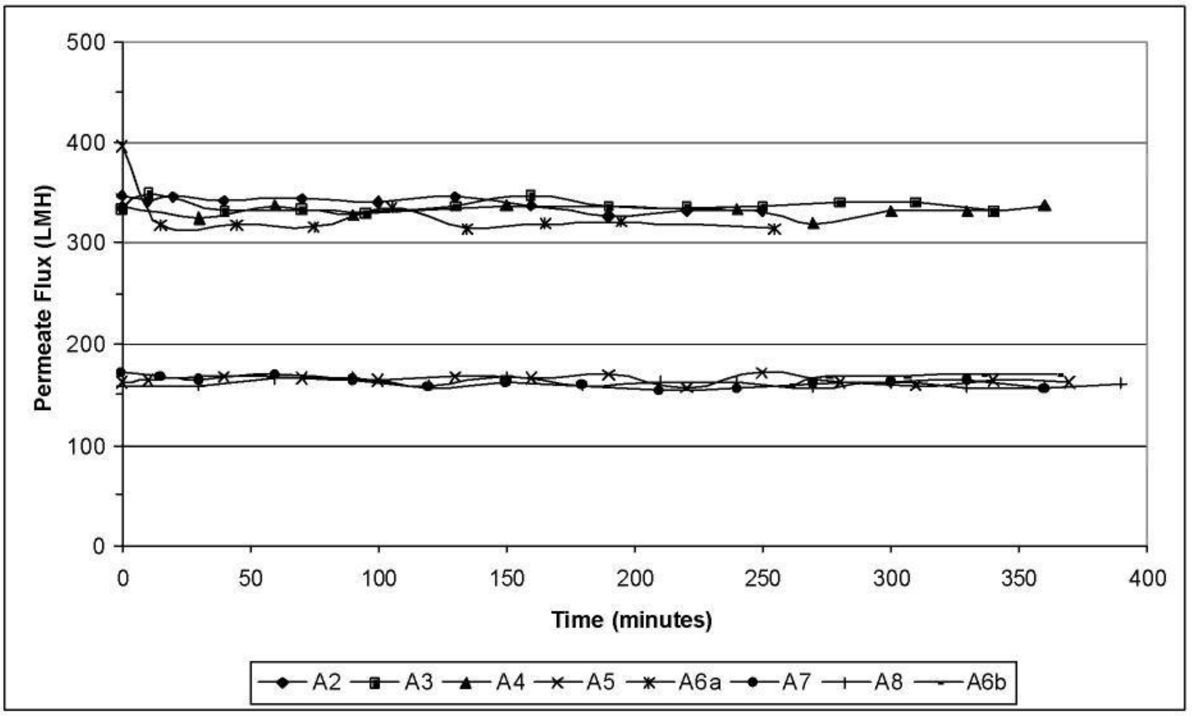

Figure 19 : Permeate flux profiles for limestone runs (@ 170 LMH and 340 LMH)

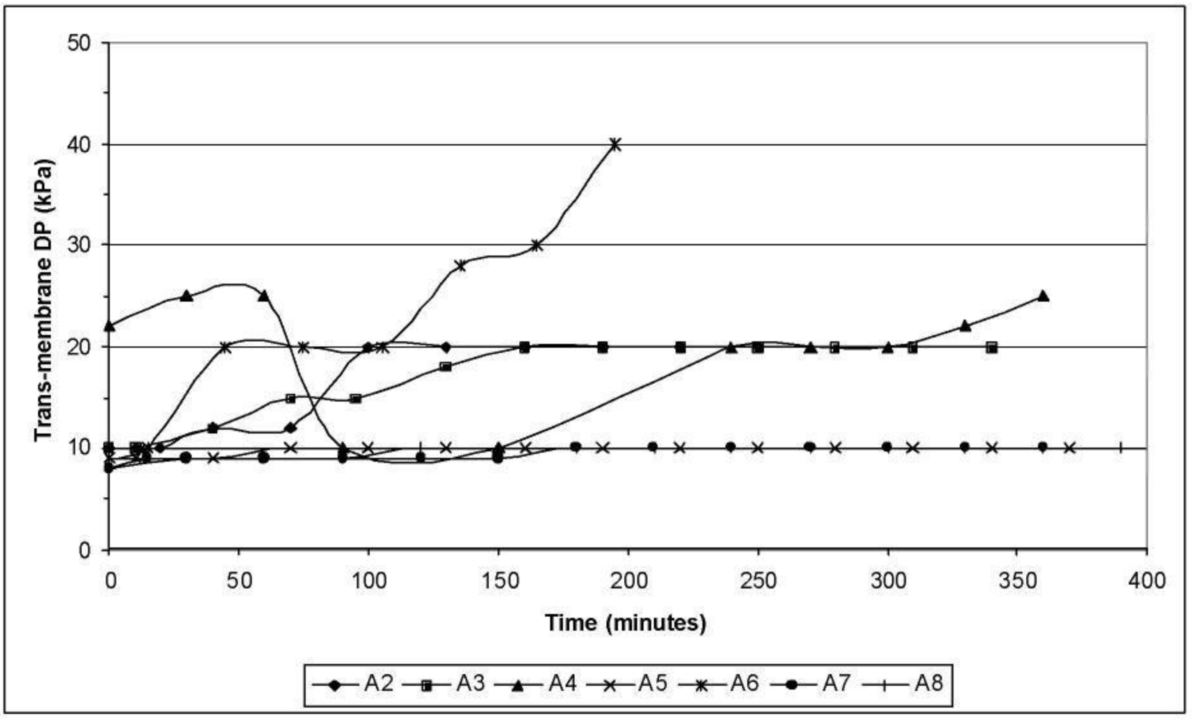

Figure 20 : Differential pressures for limestone runs

In run A6, the DP increase with time was significantly greater than that of the other runs. The reason for this is not known. However, this led to an interesting observation. Run A6 was stopped after about 200 minutes, to check whether any problem with the flowlines was causing the high DP. The module was not cleaned, but was left immersed in the feed suspension. On the following morning, the run was restarted at a lower flux. The flux and DP profiles are shown in Figure 19 (Although the run was restarted on the next morning, it is depicted as starting at 250 minutes).

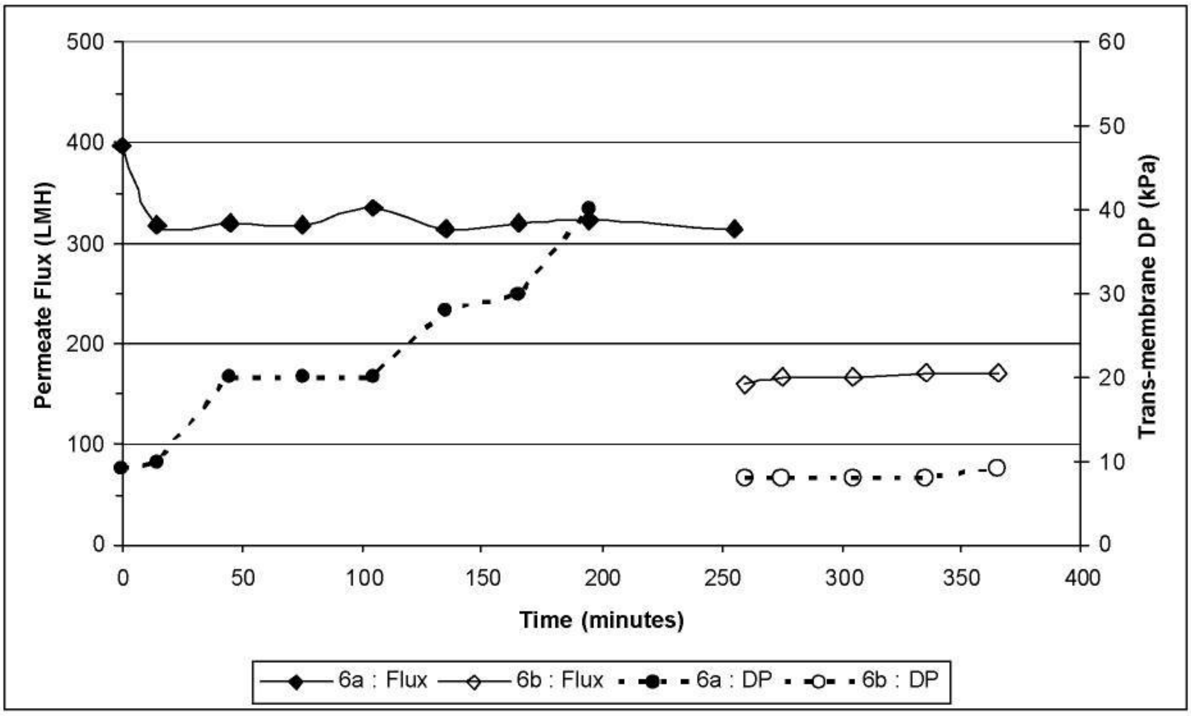

Figure 21 : Flux and DP profiles for runs A6a and A6b

In run A6a, the flux was set to 340 LMH, and the DP increased by 30 kPa in 200 minutes. In run A6b, the flux on the fouled membrane was set to 170 LMH. The DP started off at the same value as the other 170 LMH runs, and over a period of 120 minutes there was no increase in DP. Superficially this may be interpreted as running above and below the critical flux. However, the other runs at 340 LMH did not show a drastic increase in DP, and hence critical flux is clearly not a factor. A possible explanation is that the fouling layer had somehow decreased during the night. This has previously been observed on crossflow WFMF systems that were left standing without cleaning.

Unfortunately, no further drastic increases in pressure as in run A6a were experienced, and the phenomenon was not investigated further. However, it warrants further investigation as it could have implications for cleaning (noted under Recommendations).

The flux and DP profiles obtained on river water are shown in Figures 20 and 21.

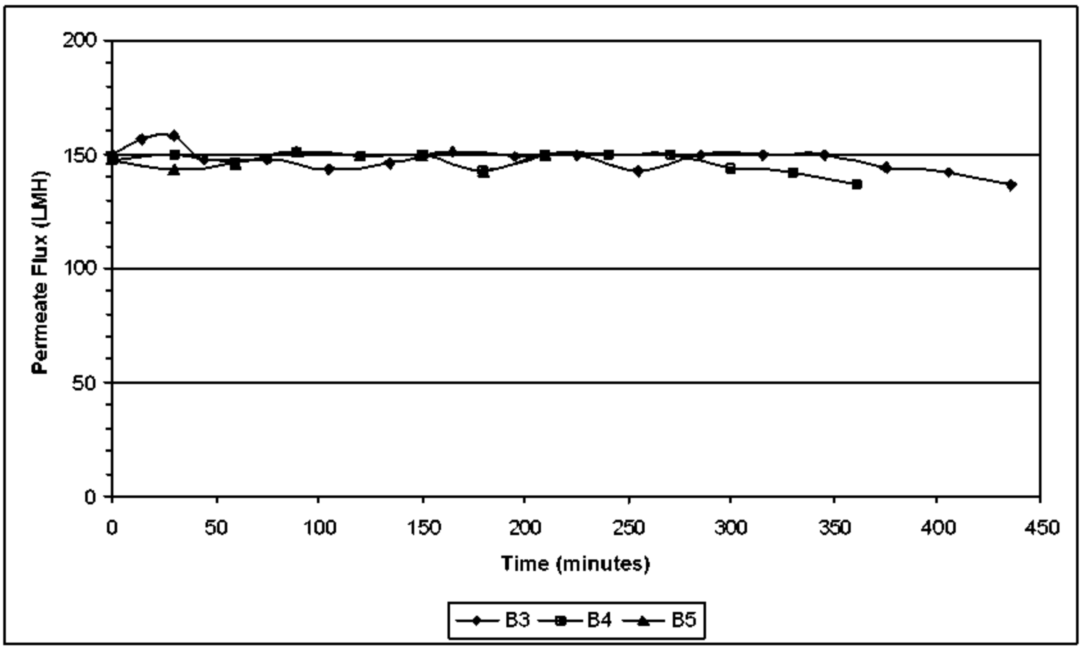

Figure 22 : Permeate fluxes on river water

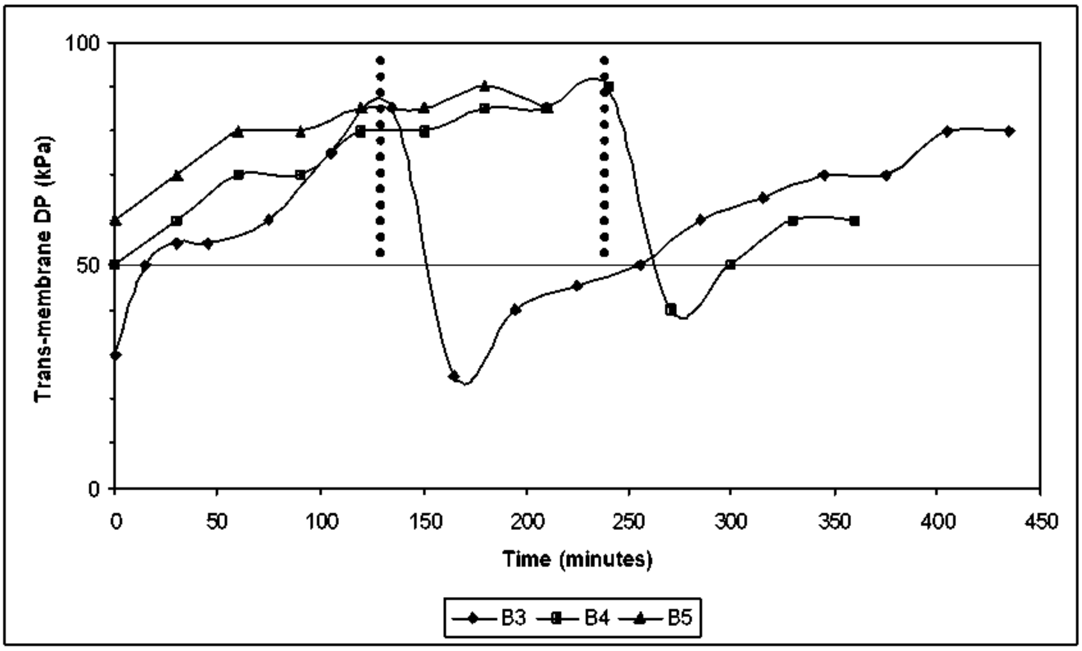

Figure 23 : Differential pressures on river water

In runs B3 and B4 the modules were removed and cleaned at 140 minutes and 240 minutes respectively. It is clear that the mechanical clean has been very effective in reducing the DP. The rate of increase in DP after the cleans is very similar to that before the cleans. The starting DPs are also substantially similar.

The fluxes and DP profiles obtained on the biological sludge at high fluxes are shown in Figure 22 and 23 respectively.

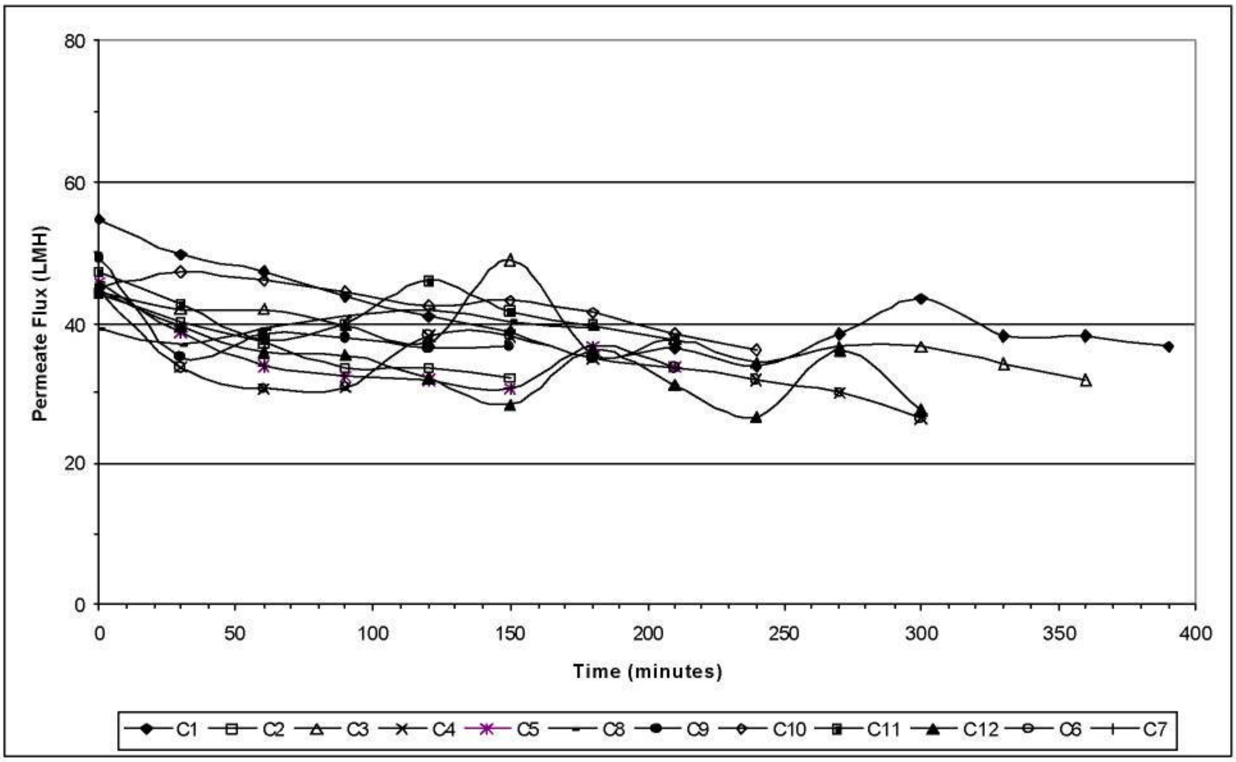

Figure 24 : Permeate fluxes on biological sludge (high fluxes)

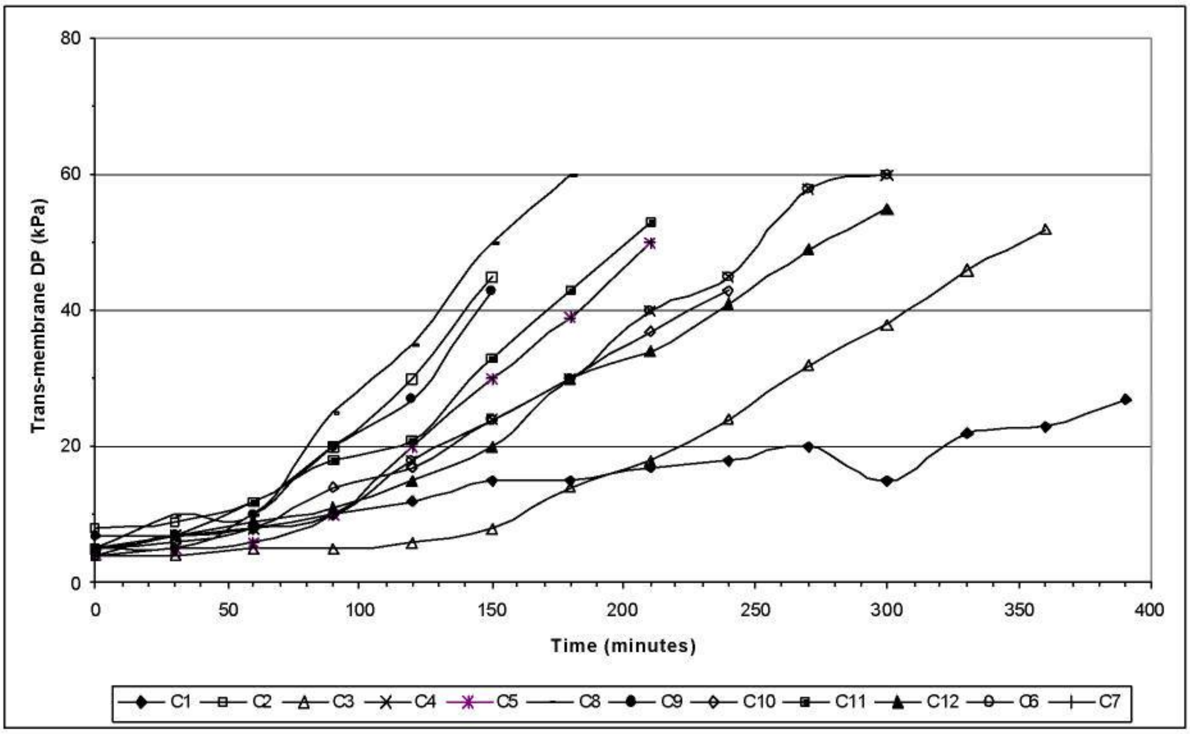

Figure 25 : Differential pressures on biological sludges (high fluxes)

The slow decrease in flux as the DP increases is a characteristic of the peristaltic pump used, since the bore of the silicone tubing in the pump decreases with increasing suction pressure. The difference in the rates of DP increase correlate reasonably with the biomass concentrations used in each run :

Run	Biomass Concentration (mg/L)
C1	2.95
C2	3.21
C3	3.02
C4	3.5
C5	4.9
C6	4.95
C7	5.2
C8	5.41
C9	5.41
C10	3
C11	3.8
C12	4.57

Figure 23 indicates clearly that the starting DP were all substantially similar. This further confirms that the mechanical cleaning of the modules was very effective in removing the fouling layer and restoring the permeability of the membranes.

6.2.2 Drying

In previous projects on WFMF, it was found that when a fouled membrane was allowed to dry, the fouling layer dried and either fell off or alternatively could be easily removed. A similar observation was made in this project. Figure 24 shows a biological reactor in operation in Prof Jacob's labs at the University of Stellenbosch. Figure 25 shows a module after the reactor was drained and the modules were allowed to dry out.

Figure 26 : Bioreactor in operation at the Institute of Polymer Science

Figure 27 : Module after drying

It is evident that the biofilm has dried and has started peeling off. This is quite remarkable, indicating that biologically fouled membranes could be restored without chemical cleaning.

None of the current commercial membrane suppliers advocate drying as a means of restoring highly fouled membranes. Presumably, drying of the fouling layer or biofilm can also occur in conventional polymeric membrane systems. However, if polymeric membranes are allowed to completely dry out, their structure is most likely to change, leaving a membrane that is almost impermeable. Conversely, the structure of the WFMF system is not changed when the membrane dries out. Hence, drying as a means of restoring highly fouled membranes could be a unique advantage of the WFMF and similar membranes.

Clearly the practicality of using drying as a means of membrane cleaning still has to be developed further. What is unequivocal, however, is that the WFMF system can be restored by allowing the system to dry out.

6.2.3 Summary

The fouling layer on the RFMF system can be removed, and the permeability of the membranes wholly restored, by mechanical cleaning. This has been confirmed for the whole range of suspensions studies, i.e. limestone, raw river water, bentonite/kaolin and activated sludge. In no instance did irreversible fouling occur necessitating a chemical clean.

It has also been shown that highly fouled membranes may be restored by allowing them to dry out. Here the fouling layer dries out and can thereafter be easily removed mechanically.

6.3 Effectiveness of backflushing

The potential of using backflushing for fouling reduction was investigated. Membranes were fouled at a constant flux, and the final DP was noted. The membranes were then backflushed by reversing the permeate flow for about five minutes. The filtration was then restarted, and the initial DP as well as the rate of increase in DP was monitored.

With the flat sheet configuration, backflushing was extremely problematic. Initially, the membranes inflated like a balloon causing mechanical damage to the module. Operating in a pulsed backflush mode partially overcame this problem. However, it was clear that backflush water was not uniformly distributed over the cross-section of the membrane, resulting in some areas of the membrane being selectively cleaned. It was obvious that these problems would be greater on larger modules, and hence further investigations on the flat sheet modules were halted.

Conversely, backflushing was significantly more successful on the compartment module. Figure 26 shows the fluxes obtained with backflushing on a bentonite/kaolin suspension, and the corresponding DP profiles are shown in Figure 27. Backflushes were performed after at

1,5 h and 3,5 h. Note that the different initial DPs (at time = 0 h) are partially due to each run being performed at a different flux.

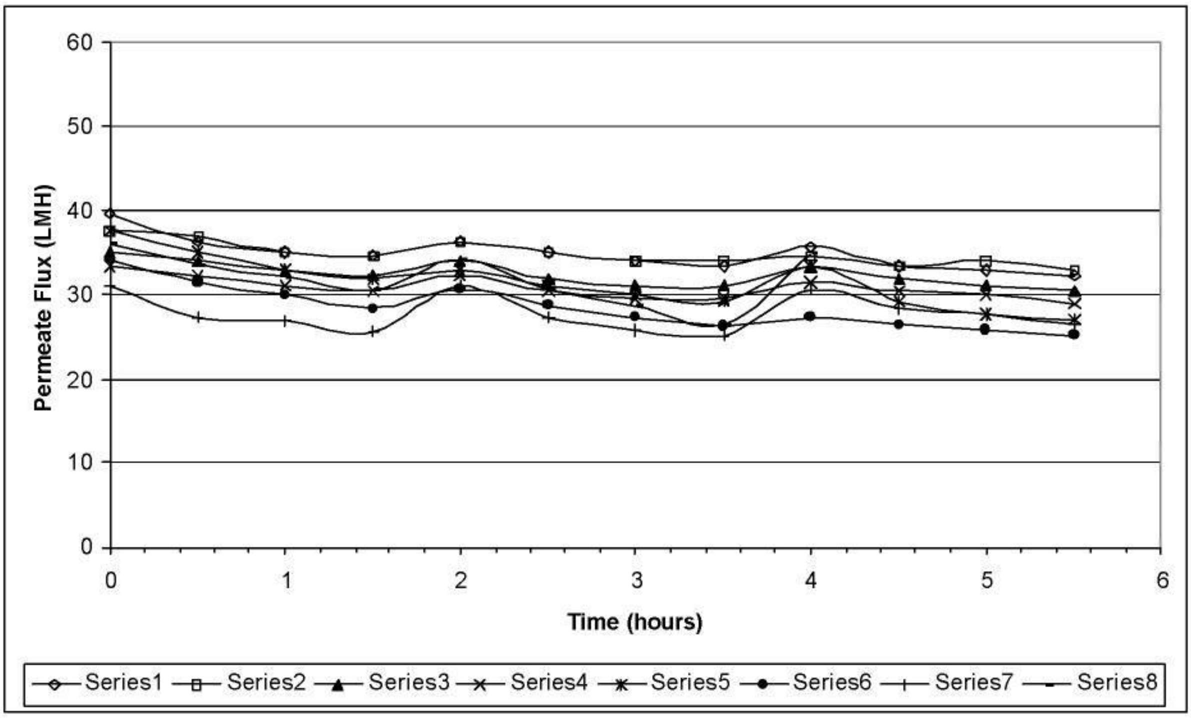

Figure 28 : Permeate fluxes for backflush runs

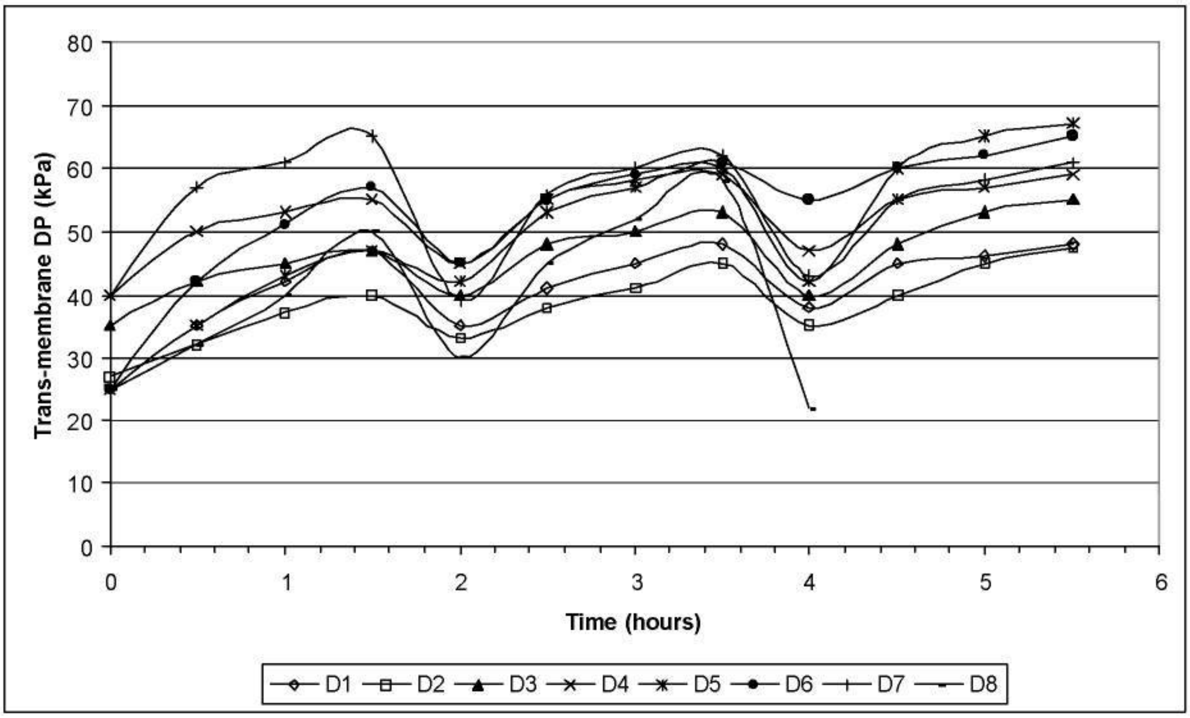

Figure 29 : DP profiles for backflush runs

It is clear that backflushing has been very successful in reducing fouling and hence the DP. Further, the rate of DP increase after each backflush is similar to that before the backflush, confirming that the fouling layer has indeed been reduced. It is also clear from Figure 27 that backflushing has been very effective in extending the effective filtration period for each run.

6.4 Operation below the critical flux

The limitations associated with performing critical flux investigations on laboratory scale apparatus have been noted in Section 3.2.2. Nevertheless, investigations into operation at sub-critical fluxes were performed to get some overview of how the RFMF system would perform in this regime.

Low flux runs were performed on a biological suspension of approximately 4 g/L biomass. Fluxes ranged from 7 LMH to 15 LMH. For reference, one run was performed at a high flux of 42 LMH. The flux profiles are shown in Figure 28, and the DP profiles in Figure 29.

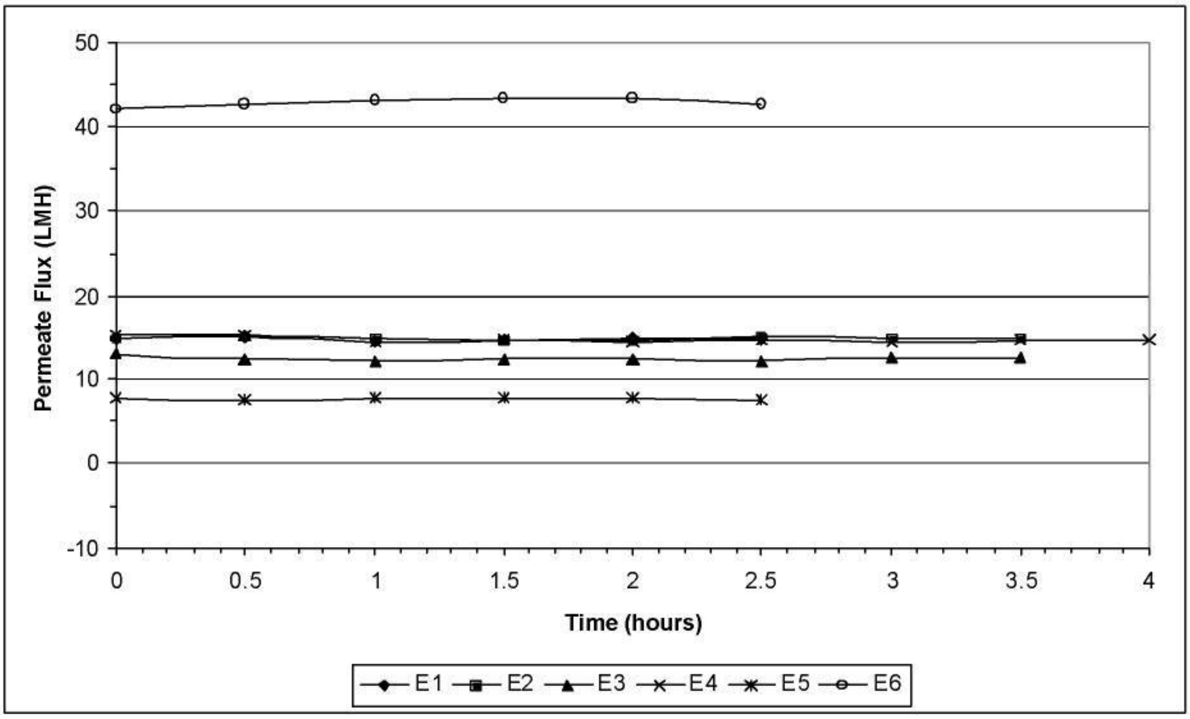

Figure 30 : Permeate fluxes for low flux runs on biological sludge

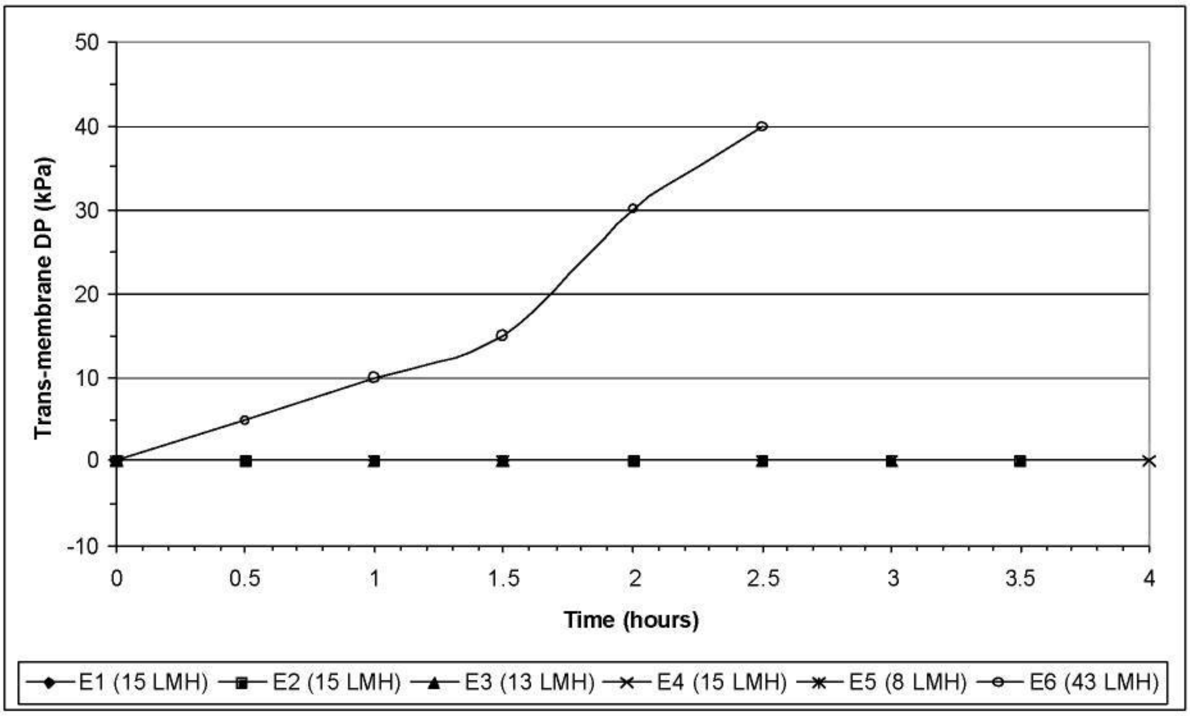

Figure 31 : DP Profiles for low flux runs on biological sludge

For all the low flux runs, the initial DP was approximately 0 kPa, and remained close to this for the duration of the run (the data points for the different runs are coincident, and hence cannot be seen easily). Conversely, at the high flux the DP increases significantly, similarly to that observed in Figure 23. For comparison, the critical flux of a Kubota module, evauated under similar hydrodynamic conditions, was 10 LMH to 15 LMH.

It is clear that the RFMF system gives the same performance at sub-critical fluxes as the current commercial IMM systems, i.e. operation at a stable DP that does not increase with time. This indicates that the RFMF system could also be designed and configured to run in the sub-critical flux mode.

6.5 Summary

The RFMF system gave permeate turbidities that could be regarded as very good to excellent. The permeate turbidities on limestone range from 0.2 NTU to 1 NTU, for a feed turbidity exceeding 999 NTU. On raw river water, a product turbidity of approximately 1 NTU is obtained for a feed of approximately 30 NTU. The product from the bentonite/kaolin trials also ranges from 0.2 NTU to 1 NTU, for a feed turbidity of around 750 NTU. For the biological sludge at high fluxes, the permeate turbidity ranges from 0.6 NTU to 1 NTU, while the product from the lower flux runs ranges from 0.8 NTU to 2 NTU. In general, the product turbidities over the range of suspensions tested is < 1 NTU, with the exceptions noted on the low flux biological sludge.

Mechanical cleaning was extremely effective in removing the fouling layer on the RFMF and wholly restoring the permeability of the membranes. This has been confirmed for the whole range of suspensions studies, i.e. limestone, raw river water, bentonite/kaolin and activated sludge. In no instance did irreversible fouling occur necessitating a chemical clean. It has also been shown that highly fouled membranes may be restored by allowing them to dry out. Here the fouling layer also dries out and can thereafter be easily removed mechanically.

Backflushing was not particularly successful on the flat sheet module, but was very effective on the compartment module. Backflushing reduced the DP, and hence extended the effective filtration period before the membrane needs to be cleaned. Further, the rate of DP increase after each backflush is similar to that before the backflush, confirming that the fouling layer has indeed been reduced. Backflushing is not currently practiced on commercial flat sheet IMM systems, and could be a potential advantage of the compartment RFMF module design.

The RFMF system gives the same performance at sub-critical fluxes as the current commercial IMM systems, i.e. operation at a stable DP that does not increase with time. This indicates that the RFMF system could also be designed and configured to run in the sub-critical flux mode, should economic or operational factors necessitate this.

7 OVERALL ASSESSMENT OF RFMF

The fundamental issue that this project needs to address is whether the RFMF system offers any particular advantage to the water treatment field, and hence whether it should be developed further.

The results obtained in this project have shown that the system adequately meets the criteria for technical viability set out in Section 2, i.e. :

(i) the system gives a very good product quality over a wide range of test suspensions

(ii) the system gives a good productivity, with fairly high fluxes being obtained for differential pressures below 0,5 bar. These fluxes can be obtained consistently and repeatibly. The system can also be run stabily at sub-critical fluxes.

(iii) The system can be easily cleaned mechanically. Highly fouled membrane can be cleaned by allowing them to dry out.

The potential advantages that this system offers over current commercial IMM systems include :

(vii) no chemical cleaning – In this project, and previous projects on WFMF, chemical cleaning was never required.

(viii) ability to be backflushed – the current commercial flat sheet IMM system does not employ backflushing for fouling reduction. In this project it has been clearly shown that backflushing is very effective in reducing fouling in the compartment model. This will enable the RFMF compartment model to operate at high fluxes, with periodic backflushing to reduce fouling.

(ix) extremely robust membranes – if a membrane is mechanically damaged and develops a hole, it can be easily patched. This cannot be done with any of the current commercial IMM membranes.

(x) operation over a wide range of feeds – previous investigations on WFMF have shown that the polyster fabric is very resistant to chemicals, and can operate at temperatures up to about 70 ^{0}C. It has been operated on feeds ranging from concentrated acids to concentrated bases, including operation on hydrofluoric acid.

(xi) Local development and production – the fabric was developed locally and is produced by a local textile company. Modules can be wholly produced locally.

(xii) Potentially inexpensive – whilst a detailed costing of modules has not been done, it is expected that the local modules would be less expensive than imported ones, particularly because of point (iv) above.

All the above point to the conclusion that the RFMF technology could be an excellent IMM system for niche applications in developing economies, as an alternative to the current IMM technologies being marketed internationally.

Potential applications for the technology include :

(v) pretreatment of high turbidity raw waters in rural/peri urban areas to remove suspended material and colloids prior to polishing and disinfection by other membranes/UV radiation/chlorine etc. There are currently no membrane technologies that are addressing this very important application in developing economies.

(vi) treatment of raw waters using gravity as the driving force. This would be particularly applicable in remote areas where no electricity is available, as well as for disaster relief (e.g. floods)

(vii) small scale membrane bioreactors for treatment of effluents at source

(viii) industrial solid-liquid separation systems

8 CONCLUSION

The overall objective of this project was to determine the technical viability and the potential of the RFMF system, and hence determine whether the technology should be developed further. Three criteria were chosen to indicate the technical viability :- separation efficiency, productivity, and ease of cleaning.

Investigations were performed on a laboratory scale immersed membrane rig on four suspensions, viz. limestone, raw river water, a bentonite/kaolin mixture and a biological sludge from an aerobic reactor. Separation efficiency was determined by measurement of the feed and permeate turbidities. Productivity was assessed by monitoring the permeate flux and operating pressure profiles, at both sub-critical and supercritical fluxes. The effectiveness of cleaning was determined by comparing the trans-membrane differential pressure (DP), at a specified permeate flux, before and after cleaning.

The RFMF system gave permeate turbidities that could be regarded as very good to excellent. The permeate turbidities on limestone range from 0.2 NTU to 1 NTU, for a feed turbidity exceeding 999 NTU. On raw river water, a product turbidity of approximately 1 NTU is obtained for a feed of approximately 30 NTU. The product from the bentonite/kaolin trials also ranges from 0.2 NTU to 1 NTU, for a feed turbidity of around 750 NTU. For the biological sludge at high fluxes, the permeate turbidity ranges from 0.6 NTU to 1 NTU, while the product from the lower flux runs ranges from 0.8 NTU to 2 NTU. In general, the product turbidities over the range of suspensions tested is < 1 NTU, with the exceptions noted on the low flux biological sludge.

Runs on limestone were performed at fluxes of 170 LMH and 340 LMH, corresponding to stable DPs of 10 kPa and 20 kPa respectively. In runs on raw river water, fluxes were maintained at 150 LMH, and the corresponding DPs increased from about 40 kPa to around 80 kPa over three hours. "High flux" runs on a bioreactor sludge were performed at approximately 45 LMH, and the DPs increased from 10 kPa to around 60 kPa over 6 hours. Bentonite/kaolin experiments were performed at 35 LMH, resulting in DPs increasing by about 25 kPa in 2 hours. "Low flux" runs on a biological sludge at fluxes ranging from 7 LMH to 15 LMH yielded no DP increases over 3,5 hours.

Mechanical cleaning was extremely effective in removing the fouling layer on the RFMF and wholly restoring the permeability of the membranes. This has been confirmed for the whole range of suspensions studies, i.e. limestone, raw river water, bentonite/kaolin and activated sludge. In no instance did irreversible fouling occur necessitating a chemical clean. It has also been shown that highly fouled membranes may be restored by allowing them to dry out. Here the fouling layer also dries out and can thereafter be easily removed mechanically.

Backflushing was not particularly successful on the flat sheet module, but was very effective on the compartment module. Backflushing reduced the DP, and hence extended the effective filtration period before the membrane needs to be cleaned. Further, the rate of DP increase after each backflush is similar to that before the backflush, confirming that the fouling layer has indeed been reduced. Backflushing is not currently practiced on commercial flat sheet IMM systems, and could be a potential advantage of the compartment RFMF module design.

The RFMF system gives the same performance at sub-critical fluxes as the current commercial IMM systems, i.e. operation at a stable DP that does not increase with time. This indicates that the RFMF system could also be designed and configured to run in the sub-critical flux mode, should economic or operational factors necessitate this.

These results indicate clearly that the criteria for technically viability have been adequately met. In addition, it is perceived that the technology would have various advantages over current commercial IMM systems. These include ÷ no chemical cleaning; ability to be backflushed; extremely robust membranes that can be easily repaired with low skills; extremely chemically resistant membranes that can operate over a wide range of feeds; local development and production; and potentially low cost technology.

Potential applications for the technology include ÷ pretreatment of high turbidity raw waters in rural/peri urban areas; treatment of raw waters using gravity as the driving force; small scale membrane bioreactors for treatment of effluents at source; and industrial solid-liquid separation systems.

All the above point to the conclusion that the RFMF technology could be an excellent IMM system for niche applications in developing economies, as an alternative to the current IMM technologies being marketed internationally. Accordingly, it is proposed that this very promising technology should be developed further.

9 RECOMMENDATIONS

It is recommended that the further development of the technology should follow the following path :

(i) Develop a standard module design. Aspects to be addressed must include :- dimensions; type of spacer; manifolding; type of epoxy to be used; and fabrication protocol.

(ii) Develop a standard membrane pack. Aspects to be addressed must include :- spacing between modules; manifolding of modules; cleaning of fouled membrane packs.

(iii) Evaluate fouling reduction strategies on a full-scale membrane pack. Strategies could include air scouring, backflushing, pulsed beds, circulating beds, circulating solids, and operation at sub-critical fluxes.

(iv) From (iii) develop a range of operating designs and operating protocols to suit the target applications.