Ultrafiltration in potable water production

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Abstract

A low-pressure membrane technology for the one-step clarification and disinfection of water for potable use is described. The membranes are operated at net driving pressures of between 30 and 40kPa. The filtered product of low turbidity was produced continuously and there was no correlation between the turbidity of the feed and that of the product. The membrane process appears to be an effective means for filtering out coliforms, to render a good quality potable water upstream of final breakpoint chlorination.

Introduction

Ultrafiltration is a pressure-driven membrane filtration operation by which submicron species are removed from water. Low- to medium-molecular mass cut-off ultrafiltration membranes not only reduce microbial counts in water but, because the pores in the membrane skin-layer are in the 10 to 50 nm size range, the membranes readily remove components that contribute to colour and turbidity in such waters. Ultrafiltration can be applied equally well, *inter alia,* to the production of potable water (Cheryan, 1986) from contaminated sources, as to the clarification and sterilisation of wine (Wang et al., 1989).

Ultrafiltration membranes have an asymmetric substructure and are generally produced from polymeric materials by a phase-inversion process (Aptel et al., 1985). During this process a homogeneous polymer solution is transformed into two liquid phases, one of which is a polymer-rich phase and the other a solvent-rich or polymer-poor phase. The polymer-rich phase coagulates during the liquid-liquid phase-separation process to form the membrane matrix, whereas the polymer-poor phase forms the interconnecting porous mass that eventually merges into the skin-layer of the membrane to create pores in the nanometre size range. The skin-layer of these integrally skinned asymmetric membranes is the most dense, while the remaining substructure becomes gradually more open-porous with increasing distance away from the skin-layer. Ultrafiltration membranes are surface filters and not depth filters; the characteristics of the skin-layer of the membrane, to a large degree, therefore define the retention properties of the membrane.

Membrane flux

The skin-sections of ultrafiltration membranes have pores or openings in the nanometre size-range, which allow transport of water under a hydrostatic driving force. Figure 1 shows the cross-section of an ultrafiltration membrane and a typical example of the asymmetric nature of the substructure of an integrally skinned membrane.

Poiseuille's law describes solvent flow (J) or product flux through the (assumed cylindrical) pores in the skin section of a membrane:

$$J = \frac{N\pi d_p^4 \Delta P}{128 \Delta x \mu}$$

where:

N = number of pores per unit area
ΔP = applied hydrodynamic pressure
Δx = pore length (including a tortuosity factor)
μ = solvent viscosity
D_p = pore dia. (average)
J = product flow

The equation shows clearly that the product flux is directly proportional to the applied pressure, porosity and the fourth power of the pore dia., and inversely proportional to the thickness of the membrane film and viscosity of a given permeating fluid.

It is evident from the equation that the product flux of a membrane with a certain fixed pore size and rated molecular mass cut-off can be increased by reducing the thickness of the membrane skin-layer (i.e., by reducing the resistance of the membrane to transport), or by increasing the number of pores in the skin-layer. However, the molecular mass cut-off performance (retention performance) of the membrane will be lowered if the pore-size of the membrane is enlarged to increase the product flux.

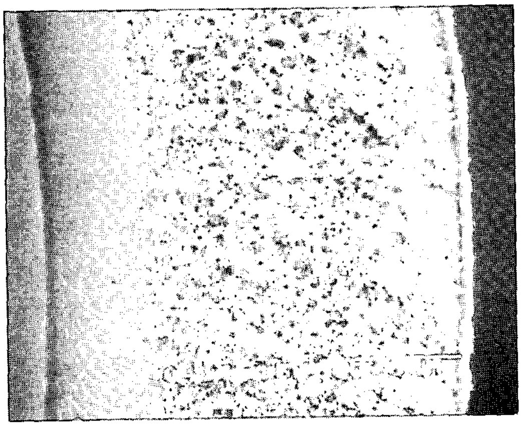

Figure 1
Typical cross-section of an ultrafiltration membrane

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Membrane types

Commercially available organic ultrafiltration membranes are produced from a number of polymers, including cellulose acetate, polyacrylates and polysulphones. The membranes are produced in tubular or flat-sheet geometries which are housed, respectively, in shell-and-tube or spiral-wrap module arrangements (Porter, 1990).

Of the different membrane geometries, the capillary type offers a viable technology for effecting clarification and disinfection filtration to provide potable water in a single-step operation. These membranes have relatively high surface area to volume packing densities, are self-supporting and have the additional hydrodynamic advantage of open-flow passages offered by tubular-type membranes (i.e. if the membranes are pressurised from the lumen side). However, although ultrafiltration may be regarded as an advanced and expensive technology, the process can be tailored and simplified to provide a filtration process that can provide water at affordable cost in the Southern African context (e.g. by the use of low operating pressures and therefore lower energy requirements; the latter is a prerequisite for the technology to have use in applications in rural or isolated areas where electrical power is not always available).

In this paper some of the recent advances that have been made towards creating a low-cost and simple ultrafiltration technology by reducing the driving force requirements of a medium molecular mass cut-off membrane, and by incorporating these membranes into low-cost modules and manifolds, are described. The results of a nine-month field test to produce potable water by a one-step clarification and disinfection operation, without the addition of chemicals, are presented.

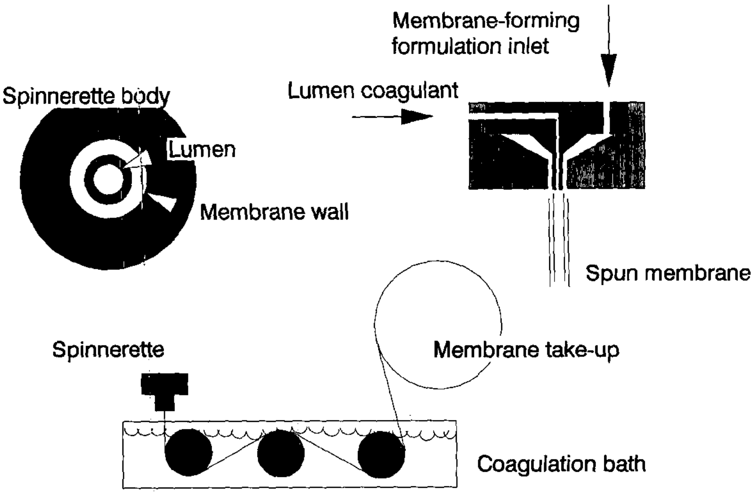


Figure 2
Capillary membrane spinning line and cross-section view of a spinning die

TABLE 1
MEMBRANE FORMULATION AND COAGULATION CONDITIONS

Component	Membrane code 748.00	767.00
Poly(ether sulphone)	26%	
Polysulphone		22%
Solvent	51%	36%
Non-solvent additive	2%	32%
Low molecular mass polymer additive	11%	10%
High-molecular mass polymer additive	10%	
Aqueous external coagulant	80% solvent	95% solvent
Pre-rinse conditioning	short air-gap	high-humidity tower
Final rinse medium	water	water

Experimental

Membrane production

Phase-inversion membranes may be made from any polymer or polymer mixture which forms a homogeneous solution under certain conditions of composition and temperature, but which separates into two phases at a different composition and temperature. In the wet-phase inversion process, water is the most commonly used non-solvent medium to bring about this change in phase.

The capillary membranes used in this investigation were made by spinning a polysulphone solution from a tube-within-tube spinnerette into a non-solvent (e.g. water) bath (Fig. 2). The bore-side of the nascent membrane was kept open by co-extrusion of a bore-side coagulant (e.g. water). By changing the membrane formulation and the composition of the coagulation bath(s), membranes with distinctly different morphologies can be produced. However, fabrication protocol can also be adjusted to bring about wanted changes in the eventual morphology of membranes (Bottino et al., 1991).

Table 1 shows two typical spinning solutions, one formulated for a polysulphone and the other for a poly(ether sulphone) ultrafiltration membrane, in which additives were used to bring about required changes in the membrane morphology. The membranes were to be internally skinned, and therefore a strong non-solvent, water, was used as the internal coagulant for both types of membrane. Had water been used as the external non-solvent coagulant, a double-skinned membrane would have resulted. However, as the aim of the study was to increase the specific flux properties of the membrane, aqueous solvent solutions (i.e. non-solvent coagulants high in solvent content) were used as external coagulants (see Table 1). The spinning techniques used to produce the two membranes was also different. Figures 3 and 4 show scanning electonmicrographs of cross-sections of the two membranes.

Figure 2 shows a side and bottom view of the spinnerette used to spin the two membrane types which had an outside dia. of ~1.8 mm and an inner dia. of ~1.2 mm.

Membrane modules and manifolding

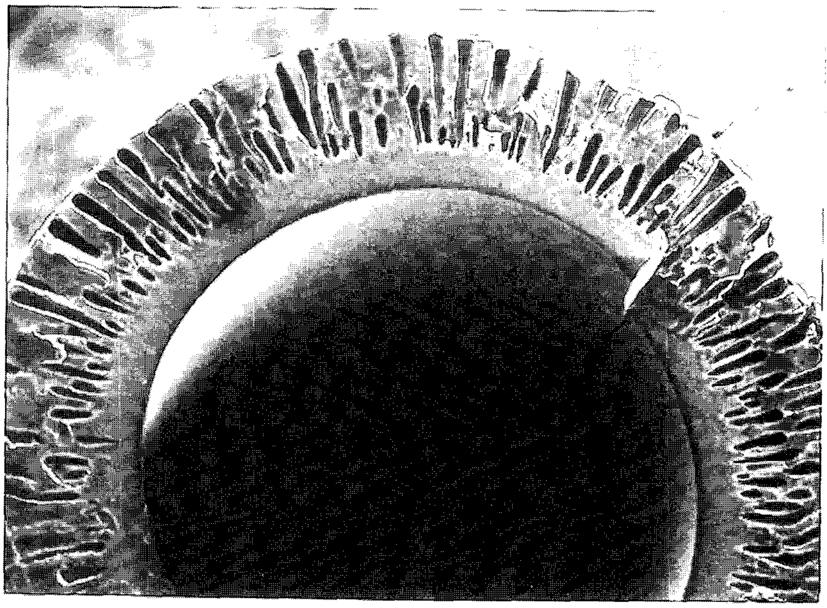
Because of their small dimensions, capillary membranes are self-supporting. The polysulphone membrane code 748 (Fig. 3) had an instantaneous internal burst-pressure >2.2 MPa, compared with >1.8 MPa for membrane code 767 (Fig. 4). Capillary membranes are usually incorporated into shell-and-tube modules and the process feed fluid flows within the membrane lumen.

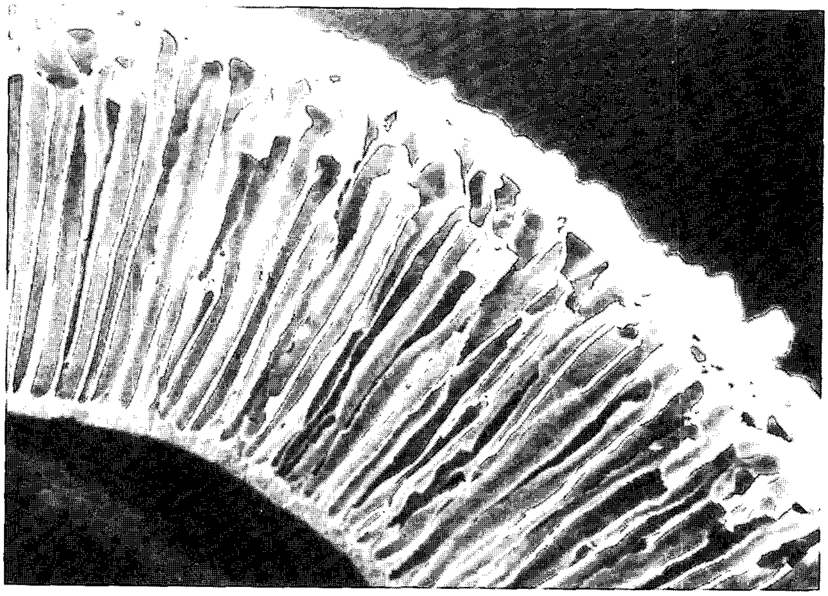
Membranes were hydraulically sealed in an axial-flow arrangement by embedding them in an epoxy tube-sheet at either end of a Class 6 u-PVC tube to form the module (Fig. 5). Each membrane module or cartridge was provided with one or two permeate outlets. The construction of the module was such that it allowed the shell side of the module to be pressurised, for example, so that the permeate flow direction through the membrane could be reversed as part of an operational strategy to backwash the membranes.

Manifolding and manifold connectors are expensive capital items. A manifold of simple design could reduce capital and module replacement costs.

One possible disadvantage of capillary membranes operating at low shear rates is that suspended solids, present in the feed water, may accummulate on the face of the tube-sheet causing membrane entrances to be bridged and eventually clogged, especially at high water recovery rates or low levels of feed pretreatment. When bridging occurs, the linear cross-flow velocity in that fibre will decrease and eventually cease. At this stage the affected membrane will effectively operate as a dead-end filter, until the complete membrane has become plugged by retained species.

One way to reduce the risk of clogging is to create shear, tangentially across the face (tube-sheet) of the module. To accomplish this, the module ends were inserted into the side-branches of T-pieces. O-rings in the tube-sheet provided a leak-free fit. The T-pieces were bolted together to provide an effective cross-face-flow manifold. Figure 6 shows a side view of the T-piece manifold connector. The inlet and outlet manifolds were anchored with wire cables to prevent telescoping under operating conditions.





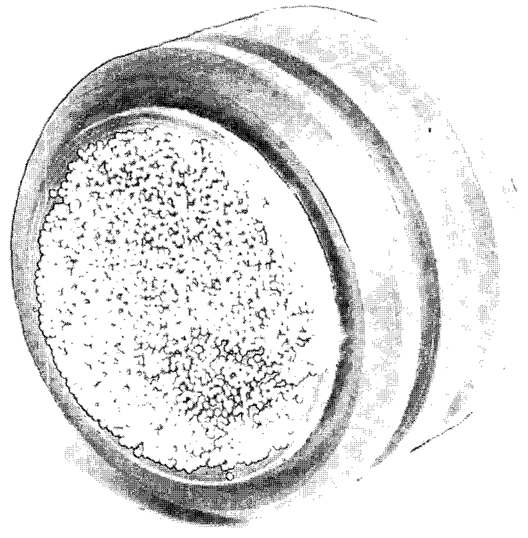


Figure 3 (top)
Electron micrograph of the cross-section of membrane code 748

Figure 4 (centre)
Electron micrograph of the cross-section of membrane code 767

Figure 5 (bottom)
Capillary membrane module tube-sheet

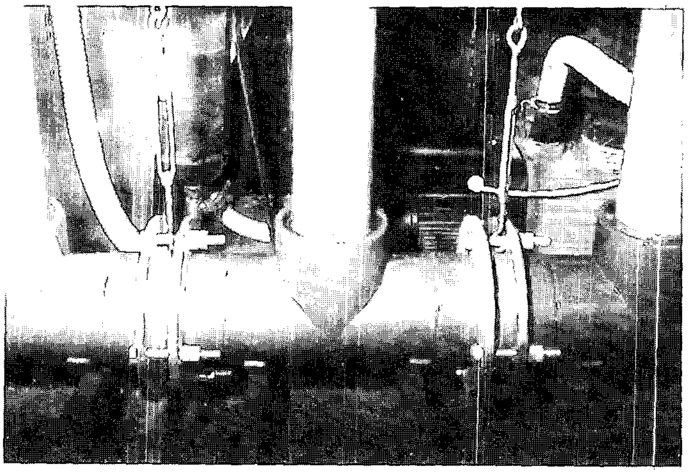


Figure 6
Manifold and module connector

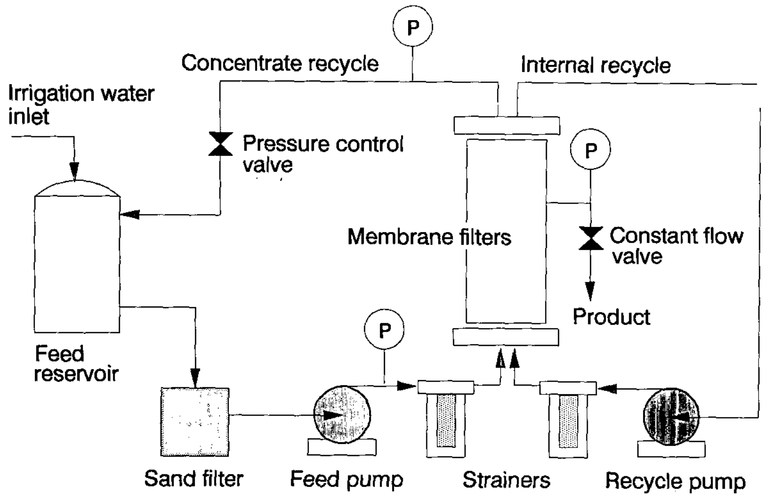


Figure 7
Layout of the pilot plant operating at Mon Villa

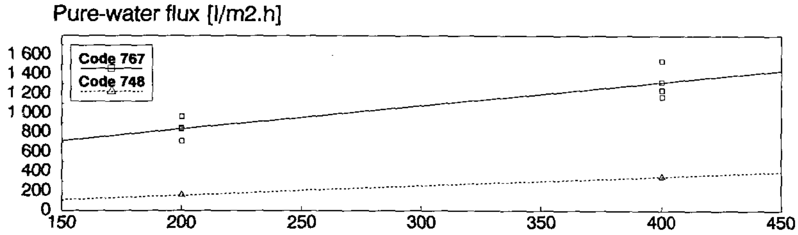


Figure 8
Pure-water flux comparison for membranes coded 748 and 767

Membrane operation

Figure 7 shows the process layout that was used in the pilot study aimed to determine the usefulness of low-pressure ultrafiltration to provide high-quality potable water. The membrane treatment scheme provided potable water for the permanent staff and workers at Mon Villa (the then seminar centre of the University of Stellenbosch), and the 100 or more delegates who used the centre on a weekly basis.

The filtration system consisted of one feed tank (4.5 k*l*) and nine similar interlinked tanks which collected the filtered product. An overflow weir between the product and the feed tank allowed the plant to be operated continuously. The system comprised two recirculation loops, the external one for the return of retentate to the feed tank, and the other was internal, for circulation of retentate to maintain minimum cross-flow velocities. Filtration through 150 μm Vortex screens was the only pretreatment prior to direct membrane filtration of water from the Helderberg Theewaterskloof irrigation scheme. No additives (chlorine or flocculants) were introduced prior to the membrane filtration operation. Breakpoint chlorination (0.2 mg/*l* residual) of the filtrate completed the treatment operation before the water was sent to the product storage tanks for distribution.

The filtration system operated on a seven-day closed-loop cycle during which all the retentate was returned to the feed tank. At the end of the seven-day period the membranes were cleaned, *in situ*, with a detergent, sequesterant and alkaline mixture using filtrate as make-up water. Shut-down time for cleaning was 45 min, whereafter the cleaning solution was rinsed from the system with feed concentrate; this operation provided an opportunity for concentrate blow-down. The overall water recovery ratio was maintained at about 96%.

Results and discussion

There was a marked difference between the pure-water flux performances of the two membrane systems 748 and 767, as depicted in Figs. 3 and 4. From the pure-water flux data shown in Fig. 8, membrane 767 clearly outperformed membrane 748. The micrographs of the cross-sections of the two membranes indicate the difference in the morphologies of the two membranes, notably the difference in density and thickness of the skin support layer.

Membrane 748 is a low-to-medium-molecular-mass cut-off membrane with a characteristic dense internal skin-layer and an outer skin-layer of lower definition. Membrane 767, on the other hand, had no external skin-layer and a relatively thin inner skin-section. The substructure of the membrane would also offer little resistance to transport. However, even although the specific pure-water flux performance of membrane 767 was greater than that of membrane 748, the question was whether the more open low-pressure membrane did in fact offer a practical alternative to conventional treatment technology. The efficiency of the new membrane 767 to clarify water, to reduce the organic and colour content, and to disinfect it to render potable water, had to be tested and demonstrated in field trials (Jacangelo et al., 1989).

Separation by an ultrafiltration membrane is effected by a sieving mechanism; in simple terms, the membrane can distinguish between dissolved and suspended species on the basis of their hydraulic radii and those of the pores in the skin of the membrane. The skin-section has pores in the 10 to 30 nm size-range which allow transport of water under a head of a few metres. (Table 2 gives the size-range of some waterborne micro-organisms for comparison). Medium molecular-mass cut-off ultrafiltration membranes can retain hydrated ions such as those of aluminium and iron, although this is not commonly observed since such retention depends on the nature of the polarised layer that forms during the filtration operation.

If waterborne micro-organisms and pathogens are to be retained by a membrane, the dimensions of the pores in the membrane must be smaller than those of the organisms (Table 2). Membranes, however, are not absolute filters because of the size distribution of the diameters of pores in the skin-layer of a membrane and there is also the possibility of imperfections in a membrane. Both factors would not only contribute to higher specific flux ratios, but also permit passage of micro-organisms through the membrane barrier. Table 3 shows the results of a microbiological analysis performed on the Theewaterskloof feed water, filtrate and recycled retentate. From these results it appears that the newly developed low-pressure membrane system is indeed capable of reducing the microbial load in the water to acceptable levels. The integrity of the membrane system and the low driving force requirements of the new ultrafiltration membrane may be the reason for this. Bacteria subdivide during growth, but under the low suction pressures at which the membranes were operated the bacteria trapped at the mouths of pores showed little tendency for "growth-through" (i.e. new organisms emerging on the other side of a pore after subdivision). One objective of the study was to reduce the use of chemicals to a minimum. For this reason the feed to the membrane plant was not prechlorinated. However, there was no evidence of slime formation (an indication of microbial fixation within the membrane system) during the trials, notwithstanding the high total heterotrophic plate count of the recirculated water. A possible reason for the absence of microbial fixation was suggested by Pohland (1995), who claimed that prechlorination may be responsible for the chemical modification of certain organic species in the feed water which render them more susceptible to biodegradation than the original starting material is. The data in Fig. 9 show the specific product flux of the membrane system. These data clearly show the typical flux behaviour of a membrane operating under gel-polarised conditions, even though the system was operated only at a net driving pressure between 3 and 6 m of water-head. The fouling, essentially caused by the accumulation of a coherent film of aquatic humic substances on the membrane surface, possibly the result of complexation with iron and aluminium and a low linear cross-flow velocity, was, however, reversible. The initial peak-value product flux was restored when the system was cleaned in a half-hour cleaning operation once a week.

Figure 10 shows the variability of the feed-water turbidity. Peak turbidity values of as high as 50 NTU were regularly obtained for the retentate, whereas values of less than 0.1 NTU

TABLE 2
SIZE-RANGE OF WATERBORNE MICRO-ORGANISMS

Waterborne micro-organisms	Size (μm)
Protozoans	
Giardia lamblia	5 - 15 by 10 - 20
ovoid cyst	6 by 10
Entamoeba histolytica	15 by 25
cyst	10 by 15
Yeasts, Fungi	1 - 10
(*Salmonella, Shigella, Legionella,* etc.)	
Spherical bacteria (cocci)	0.5 - 4
Rod-shaped (bacilli)	0.3 - 1.5 by 1 - 10
Escherichia coli (human faeces)	0.5 by 2.0
Rod-shaped curved (vibrios)	0.4 - 2.0 by 1.0 - 10
Spiral-shaped (spirilla)	<50 in length
Filamentous	<100 in length
Viruses	0.01 - 0.025
Water	0.0002

TABLE 3
MICROBIAL ANALYSIS OF FEED AND PRODUCT WATER (GRAB SAMPLE)

Potable water standard	SABS 241 (1984)	Theewaterskloof fresh feed	Feed tank (retentate)	Permeate before chlorination
Heterotrophic plate count per 1 mℓ at 35°C	100.00	188.00	34 500	44.00
Total coliform per 100 mℓ	0.00	96.00	70.00	0.00
Faecal coliform per 100 mℓ	0.00	10.00	40.00	0.00
Escherichia coliform per 100 mℓ	0.00	0.00	0.00	0.00

Samples analysed by the CSIR, Stellenbosch (29/9/95)

TABLE 4
CHEMICAL ANALYSIS OF PERMEATE PRODUCT AND FEED WATER

Sample	Filtrate	Theewaterskloof fresh feed	Feed tank (retentate)
Iron as Fe mg/ℓ	0.05	0.66	3.26
Aluminium as Al mg/ℓ	0.16	0.2	0.69
Organic carbon as C mg/ℓ	3.00	3.8	10.8

Sample analysed by CSIR, Stellenbosch (8 December 1995)

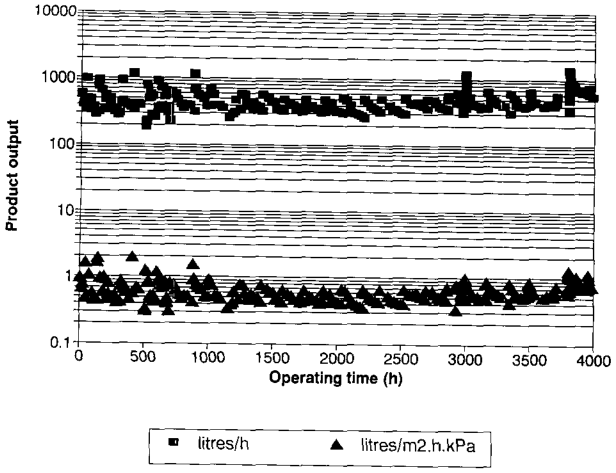


Figure 9
Flux performance of the 15 m^2 ultrafiltration plant operating on Theewaterskloof irrigation water

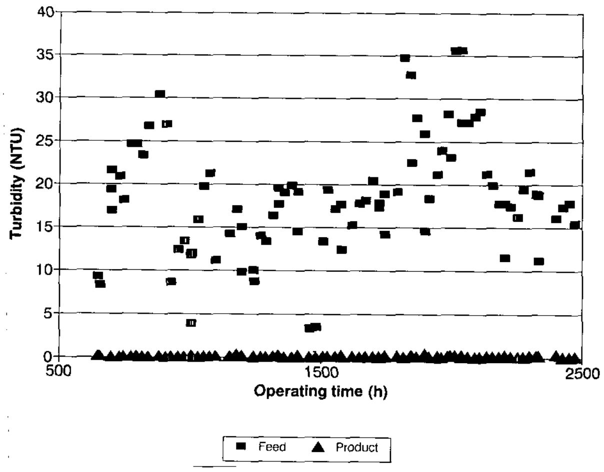


Figure 10
Turbidity reduction by ultrafiltration

were routinely obtained for the filtrate. From the data, the turbidity of the filtrate appears to be decoupled from that of the feed water, as there appears to be no apparent correlation between these turbidity values.

A chemical analysis of the process and product waters (Table 4) indicated the usefulness of ultrafiltration to lower the iron content of the water. The capability of the membrane operation to reduce the concentration levels of aluminium and total organic carbon was also demonstrated. It is, however, probable that the retention of aluminium and iron was partly due to a complexation reaction with the aquatic humic substances present at the membrane interface, as a result of concentration polarisation. This follows from the necessity to include sequestrants in the cleaning solutions.

Conclusions

The investigation provided valuable answers regarding the use of ultrafiltration in the production of water for potable use. Of importance is the indication that a new low-pressure, medium molecular mass cut-off capillary ultrafiltration membrane is capable of producing potable water from irrigation water in a one-step clarification and disinfection operation which does not necessitate the addition of any chemicals. A 15 m^2 system was operated continuously (>99% availability) for a period of nine months, at a net driving force of between of 30 and 60kPa.

The pretreatment initially consisted of a single 150mm Vortex screen. Although the ultrafiltration process operated without problems, an improvement in the specific product flux was noticed when a sandfilter was installed downstream of the Vortex strainer, and when a second strainer was installed in the recirculation loop.

The process has a capacity to reduce the iron and aluminium and also the organic load in water. The membrane process shows colour-removal potential.

The turbidity of the filtrate is decoupled from the turbidity of the feed water.

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WATER SA

ISSN 0378-4738

VOLUME 22
1996

CONTENTS AND AUTHOR INDEX

Supplement to *Water SA* Vol. 23 No.1

REFEREES

Herewith a list of referees who adjudicated the papers which appeared in the four issues published in 1996. Also included are the names of referees who reviewed papers during 1996 and found them to be unsuitable for publication. We would like to thank them all most sincerely for their willingness and for the time and effort expended in reviewing these papers in the interest of *Water SA*. Without their valued input the journal cannot exist. (The number in brackets after the name indicates the number of papers which were adjudicated by a particular referee).

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CONTENTS

Vol. 22 • No. 1 • January 1996

Vol. 22 • No. 2 • April 1996

Vol. 22 • No. 3 • July 1996

Vol. 22 • No. 4 • October 1996

Short communication

AUTHOR INDEX

Page numbers in **bold** refer to sole or first author