THE EVALUATION OF PROTOTYPE CAPILLARY ULTRAFILTRATION MEMBRANES IN APPLICATION STUDIES

by

NKH STROHWALD and A WESSELS

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by

MEMBRATEK (PTY) LTD
PO BOX 7240
NOORDER PAARL
7623

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EXECUTIVE SUMMARY

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WRC PROJECT No 397

DECEMBER 1992

PROJECT BACKGROUND

The incentive for this particular project was to extend the scope of the work on "Fixed and dynamic membrane development for water purification and effluent treatment" (WRC project no. 219), carried out by the Insitute for Polymer Science (IPS), in general. Since a co-operation agreement exists between the WRC, IPS and Membratek with regard to the exchange of information and technology on membrane systems, the project was intended to support the desired "tri-party" interaction.

The development of an internally skinned ultrafiltration capillary membrane system by the IPS (WRC project no. 387) neccessitated the evaluation of the prototype system in order to establish a first-order feedback loop for further development and refinement. The experimental work documented in this report, was designed to provide an insight into the hydrodynamic characteristics of the prototype capillary modules and to obtain information about comparative membrane performance relative to existing tubular systems. As such the project was seen to consist of two phases, *viz.* investigation and modelling of hydrodynamic characteristics and evaluation of performance through bench tests using real feedwaters.

PROJECT OBJECTIVES

The objectives of this research project were the following:

(i) To evaluate the process and design parameters which influence membrane and module performance in the capillary format;

(ii) to establish a feedback loop with regard to experimental findings in order to allow further system refinement.

These objectives were regarded as important stepping stones towards the possible future industrialisation of this technology.

RESULTS AND CONCLUSIONS

The first phase of the project on the hydrodynamic properties of the prototype capillary modules was performed in the wet-laboratory of the IPS. This laboratory was equipped with the necessary utilities, especially cooling facilities required for accurate feedwater temperature control, to ensure controlled experimental conditions as well as reliable plant monitoring and data collection.

In the second phase of the project, capillary modules were included in two application studies to evaluate their performance. The first was a pilot study concerning the use of ultrafiltration on seawater as pretreatment to reverse osmosis. This study was conducted at West Point Fishing Company, St.Helena Bay, which provided the necessary facilities. The second application study entailed the decolourising of natural water and was performed on the premises of Membratek over a period of 30 days.

HYDRODYNAMICS

The hydrodynamic characteristics of the capillary module are an important consideration in the design and configuration of a full scale ultrafiltration plant. Module pressure drop specifically has a direct bearing on the configuration of the plant, dictating attainable circulation rates, which in turn affect membrane performance and recovery rates. Experiments were therefore performed to determine the module pressure drop at different *Re*-numbers (flow velocities) in an effort to gain an insight into the hydrodynamic characteristics of these modules.

The total pressure drop consists basically of two components, *viz.* the pressure drop due to resistance against flow through the capillary (tube friction effect) and the pressure drop due to the flow distribution to and from the tube bundle (in/outlet-effect).

Using the experimentally determined pressure drop data, friction factors (f_s) were calculated with the aid of the Darcy equation for pressure losses in pipes. A pressure drop model for capillary modules which accounts for capillary diameter and number, as well as fluid characteristics in terms of *Re* number, was developed. A very good correlation was obtained between the values of the pressure drop model and those predicted by Blasius.

The experimental data and pressure drop model therefore collaborate that the Darcy equation, in conjunction with the Blasius law for f_s, may be used as a useful paractical tool to predict hydraulic pressure drop across any capillary module.

APPLICATION STUDIES

The use of prototype capillary modules in the removal of colour from natural water and the filtration of seawater, proved that similar productivity and degrees of separation to commercially manufactured tubular modules may be obtained.

Some of the advantages of the capillary modules were identified as the following:

(i) Due to the parallel configuration of the capillaries the pressure drop across the capillary bundle is considerably less than that of a series configured tubular module of similar membrane area. It is therefore possible to operate at higher linear flow velocity (or Re-numbers) for increased turbulence. This in turn results in better control of the dynamic gel-layer thickness with resultant higher flux.

(ii) The high packing density (ratio of membrane area per volume), together with low cost of construction, make this configuration a potential candidate for the clarification of a variety of feedwaters.

(iii) Membrane productivity may be increased and fouling may be controlled by adopting higher than normal flow velocities (when compared to series configured tubular modules) and standard chemical cleaning methods.

PRESENT STATE OF THE ART

The current capillary membranes and prototype modules have demonstrated possibilities in a number of applications. With minor changes to the present design and finish, these modules may be considered to be a potential commercial product.

RECOMMENDATIONS FOR FURTHER RESEARCH

Specifications for a commercial capillary module are presently being compiled. The first of such modules should be available by February 1993. The intention is to elicit reactions and comments from the market, with regard to possible export, followed by active production and marketing.

ABSTRACT

The hydrodynamic behaviour and performance of prototype capillary ultrafiltration modules were investigated.

It was found that module pressure drop may be predicted by a combination of the Blasius and Darcy relationships for friction losses through pipes. Although not exact, the predictions may be used as a practical tool in the design of capillary systems.

The prototype capillary modules showed performance characteristics similar to tubular units, with the major advantage of lower pressure drop at increased flow velocities. This may be exploited to achieve better control of the dynamic gel-layer thickness with positive effects on membrane flux.

ACKNOWLEDGEMENTS

The research results presented in this report emanated from a project funded by the Water Research Commission, entitled:

The evaluation of prototype capillary ultrafitration membranes in application studies

The financing of the project by the Water Research Commission and the co-operation of West Point Fishing Co. as well as the efforts of the Membrane Research Team of the Institute for Polymer Science are gratefully acknowledged.

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LIST OF SYMBOLS AND ABBREVIATIONS

CaOCl	Calcium hypochloride
CIP	Cleaning in place
EDTA	Ethylene diamine(tetra-acetic) acid
HCl	Hydrochloric acid
H_2SO_4	Sulphuric acid
MEMTUF	Trade name for low-cost UF system
MMCO	Molecular mass cut-off
NaOH	Caustic soda
RO	Reverse osmosis
SWUF	Trade name for low-cost UF system designed for seawater pretreatment
UF	Ultrafiltration

$\blacktriangle P_f$	Pressure drop due to friction (Pa)
d	Tube diameter (m)
f_s	Stanton friction factor
g	Mass flowrate (kg/s)
l	Tube length (m)
Re	Reynolds number
u	Linear flow velocity (m/s)
μ	Kinematic viscosity ($kg.m^{-1}.s^{-1}$)

SECTION ONE : INTRODUCTION

1.1 BACKGROUND

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The objectives of this research project were the following:

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SECTION TWO : EXPERIMENTAL

The first phase of the project on the hydrodynamic properties of the prototype capillary modules was performed in the wet-laboratory of the IPS. This laboratory was equipped with the necessary utilities, especially cooling facilities required for accurate feedwater temperature control, to ensure controlled experimental conditions as well as reliable plant monitoring and data collection.

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2.1 EXPERIMENTAL EQUIPMENT

2.1.1 HYDRODYNAMICS

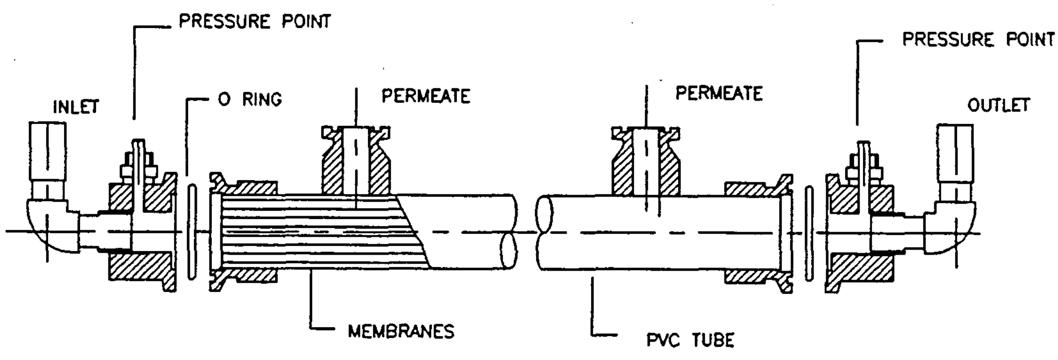
Capillary Modules

Prototype capillary modules of various lengths and different numbers of capillaries were manufactured to investigate the effects of friction and in-/outlet losses on overall module pressure drop. Details about the various module designations and particulars are given in Table 2.1 below. Figure 2.1 gives a schematic diagram of the modules, showing in-/outlet details and positions of pressure take-off points.

TABLE 2.1 : PHYSICAL CHARACTERISTICS OF CAPILLARY MODULES USED IN HYDRODYNAMIC EXPERIMENTS

Module designation	No. of capillaries	Module length
N100L325	100	325 mm
N100L410	100	410 mm
N100L615	100	615 mm
N150L300	150	300 mm
N150L405	150	405 mm
N150L610	150	610 mm

FIGURE 2.1 : SCHEMATIC DIAGRAM OF CAPILLARY MODULE



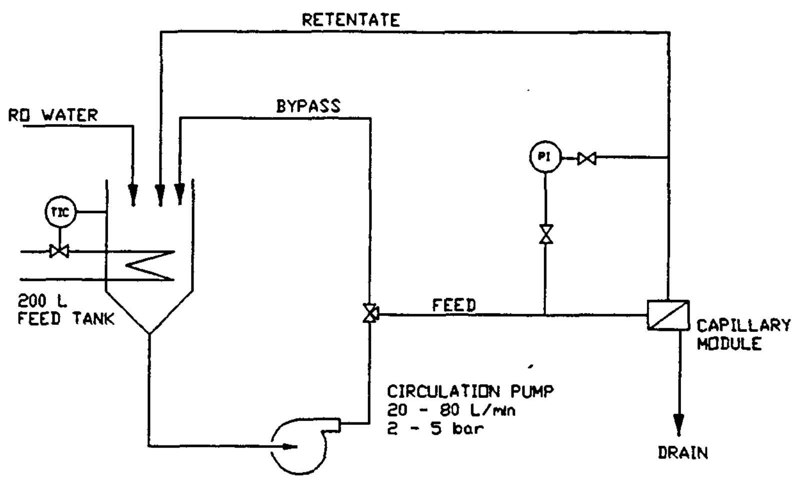
Test Bench

The capillary test system, schematically depicted in Figure 2.2, comprised a batch tank, feed pump and prototype capillary modules. RO water produced from municipal supply, was used as medium in the experimental runs to minimise variations in viscosity and physical characteristics between different runs. The temperature of the water in the 200 l feed tank was controlled by a temperature controller acting on a solenoid valve in the cooling water circuit. A master gauge with an accuracy of 0,5% was used to measure the pressure at the inlet and outlet of the modules in the higher pressure ranges. A mercury manometer was used in the lower pressure ranges to reduce experimental error. The linear flow velocity in the capillaries was varied by adjusting the by-pass valve on the discharge side of the circulation pump.

2.1.2 APPLICATION : NATURAL WATER

The ultrafiltration system used in colour removal experiments consisted of a feed tank, transfer pump, buffer tank, circulation pump and UF capillary module (refer Figure 2.3). The water level in the buffer tank was maintained with water supplied from the feed tank by the transfer pump . The temperature of the feedwater to the capillary module was controlled by circulating tap water through a cooling coil in the feed tank. The recovery of the system was controlled by feeding and bleeding in the required proportions. Pressure gauges on the in- and outlet sides of the capillary module indicated the operating pressure and pressure drop across the module.

FIGURE 2.2 : LINE DIAGRAM OF EXPERIMENTAL EQUIPMENT USED FOR DETERMINATION OF CAPILLARY MODULE HYDRODYNAMICS



2.1.3 APPLICATION : SEAWATER

Capillary modules used in the experiment had membranes with typical external and internal diameters of 1,8 and 1,5 mm respectively. Bundles of 200 to 250 capillaries were housed in clear uPVC tubes to give an overall module length of 1 m. The internally-skinned membranes were end-potted in a tube-and-shell arrangement with a special epoxy which adheres well to PVC.

The 719-series UF membranes used in the MEMTUF modules had a molecular mass cut-off (MMCO) of 40 000 dalton while two types were used in the SWUF modules, a similar 719-series 40 000 MMCO membrane and a 442-series membrane of 6 000 MMCO. The membranes of the capillary modules had an effective MMCO of 4 000 when tested on an aqueous solution of PEG.

The various membrane systems were skid-mounted to allow simultaneous evaluation of the different configurations. The test equipment was installed on a jetty of West Point Fishing Co. where seawater could be obtained from existing intake piping. The raw seawater was first screened to 300 μm before being subjected to dual-media filtration. Filtered seawater was collected in a 200 l buffer tank from which it was distributed to the various modules by means of a centrifugal pump and ring manifold. Take-off points for the individual modules were provided with pressure gauges for the determination of operating pressure. The mechanical line diagram for the experimental skid is illustrated in Figure

2.4. A second 200 μm screen was installed ahead of the capillary module to prevent physical blocking of the capillaries by solids (e.g. carry-over grit from the sand-filter).

FIGURE 2.3 : SCHEMATIC OF EXPERIMENTAL EQUIPMENT USED IN COLOUR REMOVAL FROM WATER

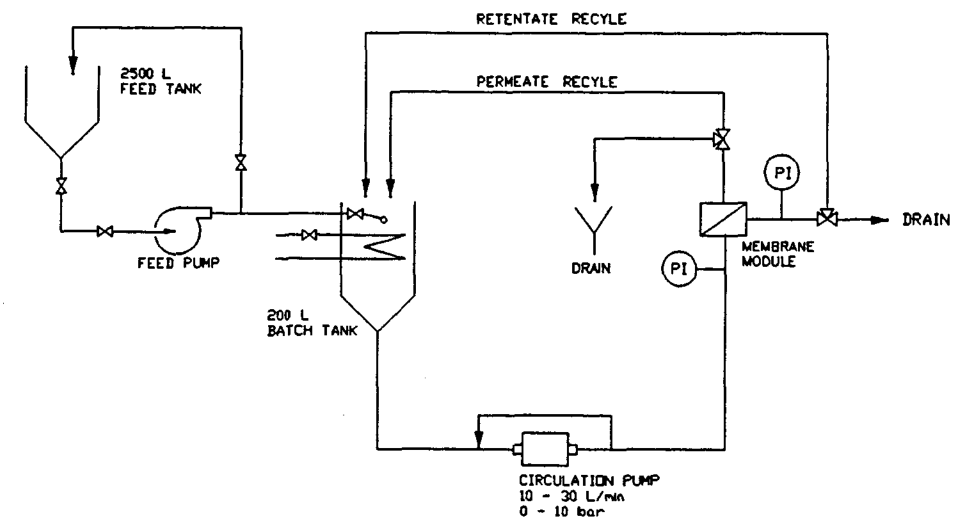
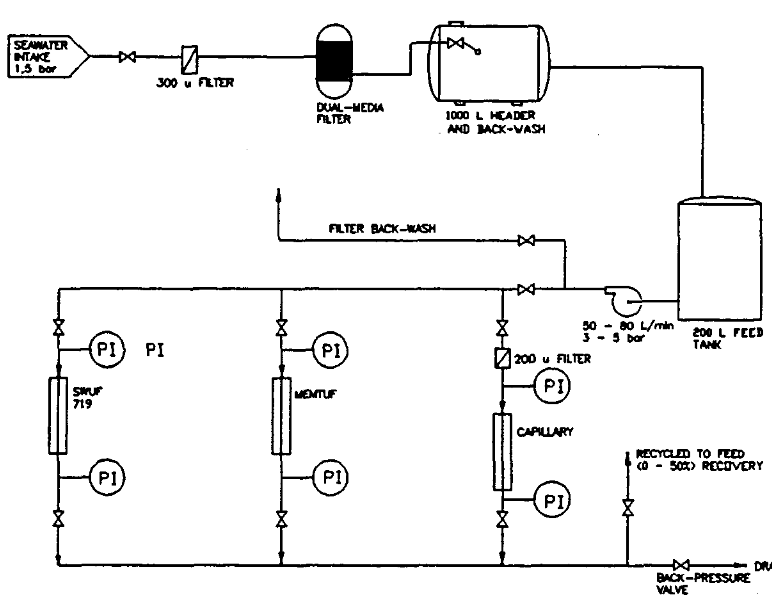


FIGURE 2.4 : SCHEMATIC OF EXPERIMENTAL EQUIPMENT USED FOR FILTRATION OF SEAWATER



2.2 METHODS

2.2.1 HYDRODYNAMICS

The pressure drop across the capillary modules was calculated as the difference between the in- and outlet pressures. Pressure readings in the lower ranges were made with the aid of a mercury manometer in order to verify master gauge readings and eliminate possible errors at low pressure drop values.

Retentate flowrates were determined by time/volume measurements and taken to be equivalent to the feed flowrates. This assumption was valid for practical purposes since the recovery per pass was virtually zero (recovery $< 1\%$).

RO permeate, produced from municipal potable supply, was used as feedwater. Combined with accurate temperature control this served to minimise possible variations in density and viscosity which affect the determination of the *Re*-number. With density and viscosity of the feedwater assumed to be constant, the *Re*-number was taken to be proportional to linear flow velocity and capillary diameter only.

2.2.2 APPLICATION : NATURAL WATER

The natural water was first concentrated to the 90% recovery level with consecutive batch runs. In these runs the permeate was discarded, while all the retentate was recycled to the feed tank. At the end of a concentration cycle the feed tank was refilled with fresh feedwater and the process repeated Once a recovery of 90% had been achieved, the system was operated in a feed-and-bleed mode on a continuous basis. This was done by continuously measuring and balancing the volume of permeate which was removed and the volume of fresh natural water being added. Operating pressures and flux values were logged twice a day. Colour readings of feed and permeate samples were determined with a Hach photometer.

2.2.3 APPLICATION : SEAWATER

Flux values of the various membrane systems were recorded during frequent site visits. A recovery of approximately 50% was maintained by returning a portion of the combined retentate to the buffer tank while balancing the remainder of the retentate flow with the combined permeate flow, both of which were routed to waste (refer Figure 2.4). Each membrane system was operated at conditions which were considered to be optimum for the particular configuration (refer to Table 2.2) and at the prevailing ambient seawater temperature.

TABLE 2.2: CHOSEN OPERATING CONDITIONS FOR SEAWATER FILTRATION TRIAL

Parameter	Memtuf	SWUF	Capillary
Inlet pressure (kPa)	200	300	200
Outlet pressure (kPa)	50	50	50
Linear flow velocity (m/s)	2,5	1,8	2,8
Membrane area (m^2)	0,4	3,0	0,4

SECTION THREE : RESULTS AND DISCUSSION

3.1 HYDRODYNAMICS

The hydrodynamic characteristics of the capillary module are an important consideration in the design and configuration of a full scale ultrafiltration plant. Module pressure drop specifically has a direct bearing on the configuration of the plant, dictating attainable circulation rates, which in turn affect membrane performance and recovery rates. Experiments were therefore performed to determine the module pressure drop at different *Re*-numbers (flow velocities) in an effort to gain an insight into the hydrodynamic characteristics of these modules.

3.1.1 EXPERIMENTAL PRESSURE DROP AND CURVE FITTING

The experimental results of the module pressure drop determinations that were obtained at IPS are presented in Figures 3.1 to 3.6. These graphs show that the manometer readings corresponded well with those of the master gauge. However, at lower pressures the master gauge seems to introduce a certain degree of error, resulting in lower than actual pressure drop values, as may be seen from the results for the N150L300 capillary module which are presented in Figure 3.4. To simplify data processing no correction factor was used and the average pressure drop was used for further calculations. Flowrates through the capillary tubes were transformed to *Re*-numbers to result in dimensionless values. It was necessary to compare the pressure drop values of the different modules at the same *Re*. To accomplish this, curves dependent on *Re* were fitted to the data. Curve fitting was done with the "CurvetB1" programme (a Shareware product) which fits 25 different functions to a particular data set by means of the least squares method. It was found that the second order polynomial functions resulted in the best average fit for all the data sets. A list of relevant quadratic functions fitted to the experimental data is presented overleaf (Table 3.1). Further data manipulation was performed with the aid of these fitted curves. Figures 3.1 to 3.6 display the measured and curve-fitted pressure drop values at different *Re*-numbers.

TABLE 3.1 : DETAILS OF QUADRATIC FUNCTIONS FITTED TO EXPERIMENTAL PRESSURE DROP DATA

Figure	Module	Fitted Curve	R^2
3.1	N100L325	$-0,8398 + 3,998.10^{-3}Y + 1,568.10^{-6}Y^2$	0,99
3.2	N100L410	$-5,8306 + 8,409.10^{-3}Y + 1,485.10^{-6}Y^2$	0,95
3.3	N100L615	$-3,7890 + 6,603.10^{-3}Y + 3,201.10^{-6}Y^2$	0,99
3.4	N150L300	$+1,3210 - 4,536.10^{-3}Y + 3,550.10^{-6}Y^2$	0,97
3.5	N150L405	$+1,2784 + 7,154.10^{-4}Y + 2,574.10^{-6}Y^2$	0,99
3.6	N150L610	$-0,1430 + 3,690.10^{-3}Y + 3,102.10^{-6}Y^2$	0,98

FIGURE 3.1 : EXPERIMENTAL AND FITTED PRESSURE DROP DATA AT VARIOUS *Re*-NUMBERS - MODULE N100L325

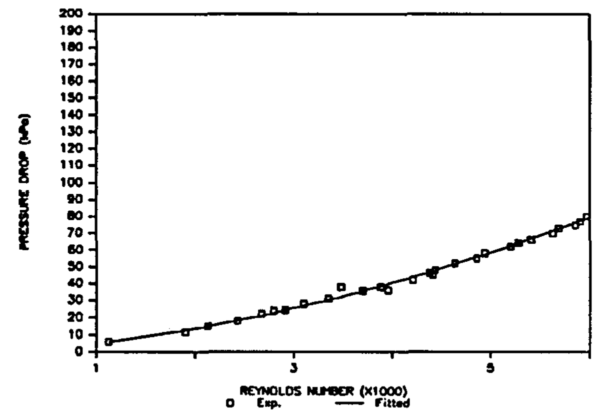


FIGURE 3.2 : EXPERIMENTAL AND FITTED PRESSURE DROP DATA AT VARIOUS *Re*-NUMBERS - MODULE N100L410

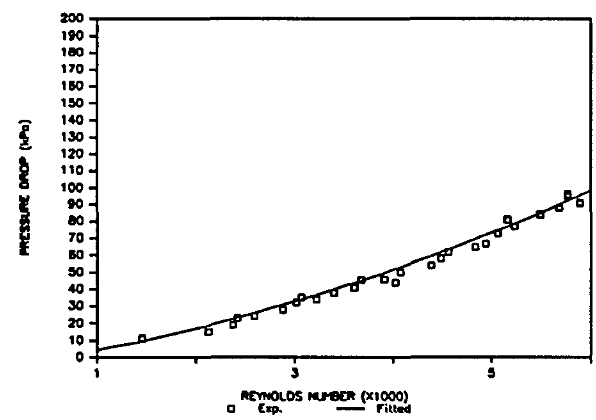


FIGURE 3.3 : EXPERIMENTAL AND FITTED PRESSURE DROP DATA AT VARIOUS *Re*-NUMBERS - MODULE N100L615

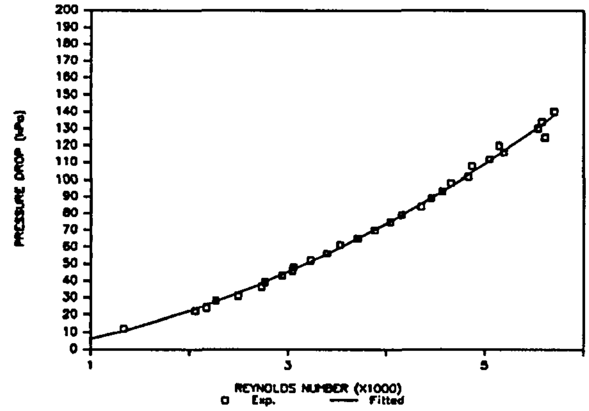


FIGURE 3.4 : EXPERIMENTAL AND FITTED PRESSURE DROP DATA AT VARIOUS *Re*-NUMBERS - MODULE N150L300

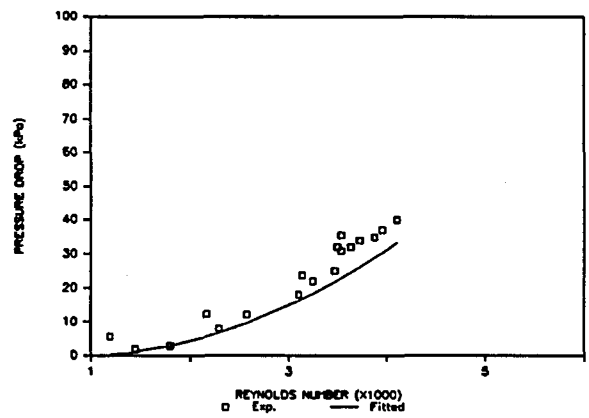


FIGURE 3.5 : EXPERIMENTAL AND FITTED PRESSURE DROP DATA AT VARIOUS *Re*-NUMBERS - MODULE N150L405

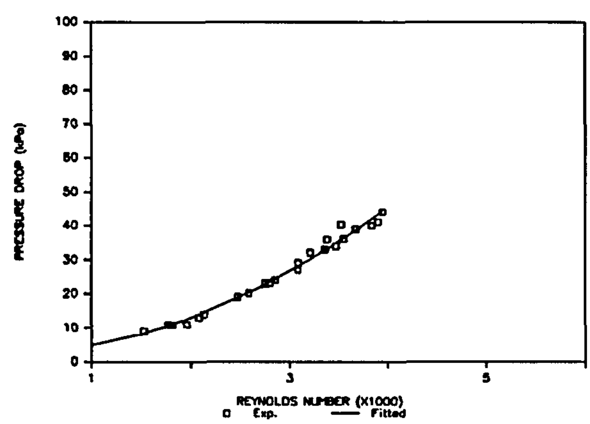
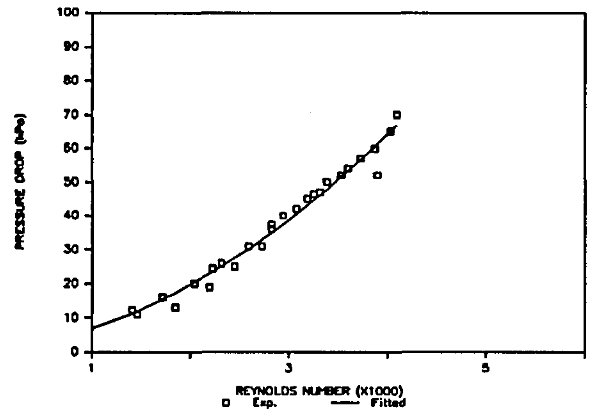


FIGURE 3.6 : EXPERIMENTAL AND FITTED PRESSURE DROP DATA AT VARIOUS *Re*-NUMBERS - MODULE N150L610



3.1.2 DATA MANIPULATION

As may be expected with flow through a pipe, the pressure drop across the modules increased exponentially with an increase in feed flowrate or *Re*-number, as illustrated by Figures 3.1 to 3.6. The total pressure drop consists basically of two components, *viz.* the pressure drop due to resistance against flow through the capillary (tube friction effect) and the pressure drop due to the flow distribution to and from the tube bundle (in/outlet-effect). This may be expressed as follows:

$$\Delta P_{tot} = \Delta P_{length} + \Delta P_{ends} \qquad (1)$$

The configuration of the capillary modules does not lend itself towards the practical measurement of these individual components, therefore the approach was to isolate the tube friction component (ΔP_{length}) theoretically or empirically. The complement of the measured pressure drop (ΔP_{tot}) then has to be an indication of the in/outlet-pressure drop component (ΔP_{ends}). Because of the complexity associated with the flow distribution problem (parameters like %flow area, pitch, pattern, capillary diameter, *etc.*) no attempt was made to mathematically describe the ΔP_{ends}-component, either theoretically or empirically. It will be shown later that the in/outlet component is only a fraction of the measured pressure drop and that ΔP_{ends} may be ignored for practical reasons.

Tube Friction Component (ΔP_{length})

It was reasoned that if modules of different length, but with identical distribution heads, number of capillaries, capillary diameter and experimental set-up are used, then the increase in pressure drop due to an increase in module length must be a pure tube friction component. The six modules with two different bundles of respectively 100 and 150 capillaries, each in three different lengths (refer to Table 2.1) were built to conform to the above criteria. The pressure drop per unit length, $\Delta P/\Delta L$ was calculated at various *Re* by subtracting the fitted pressure drop values at a specific *Re* (refer Figures 3.1 to 3.6) of the three N100 and three N150 modules from one another. These values are shown in Figures 3.7 (ΔP/ΔL100) and 3.8 (ΔP/ΔL150). Ideally, the data points of the three lines in each figure should be represented by a single line, to indicate that all other parameters, including length, are constant and that ΔP_{length} is only a function of velocity. Given that all parameters, except velocity, are constant one would also expect the lines of Figures 3.7 and 3.8 to be identical, as the effect of number of capillaries is already accounted for in the velocity and therefore *Re*. Possible reasons for the divergence of the three lines in both graphs are the following:

1) Experimental errors (inaccurate pressure readings and non-linear calibration of measurement equipment).
2) The relationship between pressure drop and module length is not linear as assumed.
3) Inaccurate curve fitting. Differences between fitted values are used, with all the fitted curves being second order polynomial functions of *Re*. The difference between a slightly too convex curve and a slightly too concave curve will substantially compound the effect.
4) Modules are not identical, therefore parameters (non-constants) other than length determine the pressure drop.

Darcy Equation

Assuming that flow through the capillaries is steady state, the medium is incompressible and the capillary is hydraulically smooth, then Darcy's equation *(Perry, 1963)* may be used to describe the tube friction effect:

$$\Delta P_f = (f_s \, l \, g \, u^2) / (2d) \qquad (2)$$

with

$$Re = (g \, u \, d) / \mu \qquad (3)$$

combination of equations *(2)* and *(3)* yields the Stanton friction factor, f_s as a function of *Re*:

$$f_s = [(2 \, d^3 \, g) / (Re^2 \, \mu^2)] \, \{(P_1 - P_2) / (l_1 - l_2)\} \qquad (4)$$

The Stanton friction factor, f_s is thus a function of *Re* and $\Delta P/\Delta L$ if all other parameters remain constant. No Stanton friction factors or "surface roughness ϵ"

figures for polyethersulphone membranes could be found in a literature study. The Stanton friction factor therefore had to be determined from the experimental data. The means of the three respective trends in Figures 3.7 and 3.8 were used as ▲*P*/▲*L* values and f_s was thus determined semi-empirically from the experimental data.

FIGURE 3.7 : PLOT OF CALCULATED LENGTH COMPONENT OF PRESSURE DROP - ▲P/▲L100

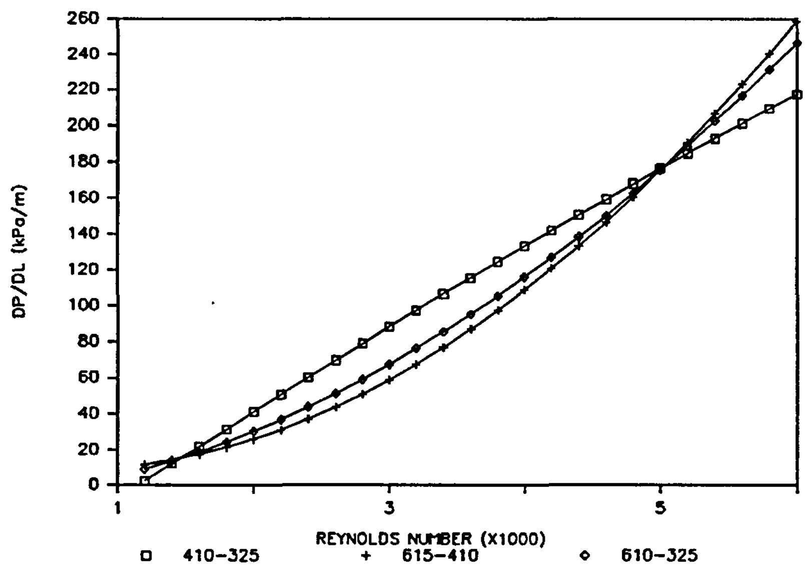
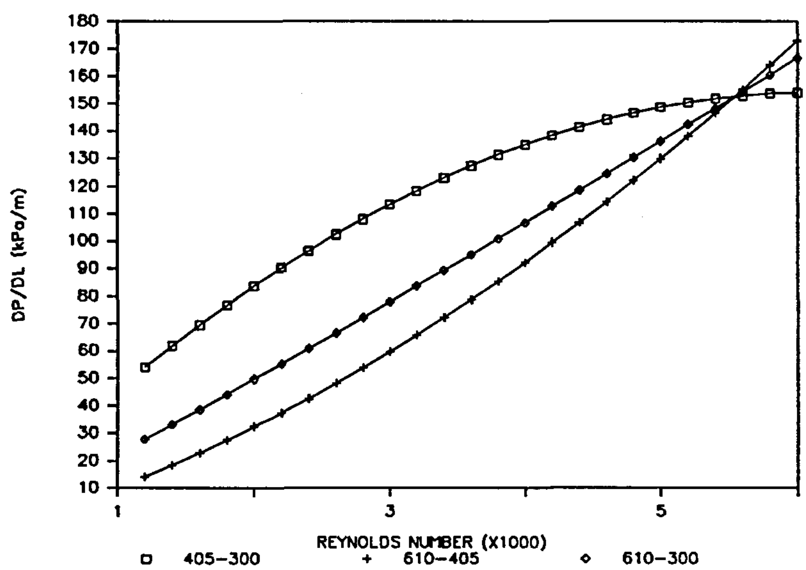


FIGURE 3.8 : PLOT OF CALCULATED LENGTH COMPONENT OF PRESSURE DROP - ▲P/▲L150



Blasius Equation

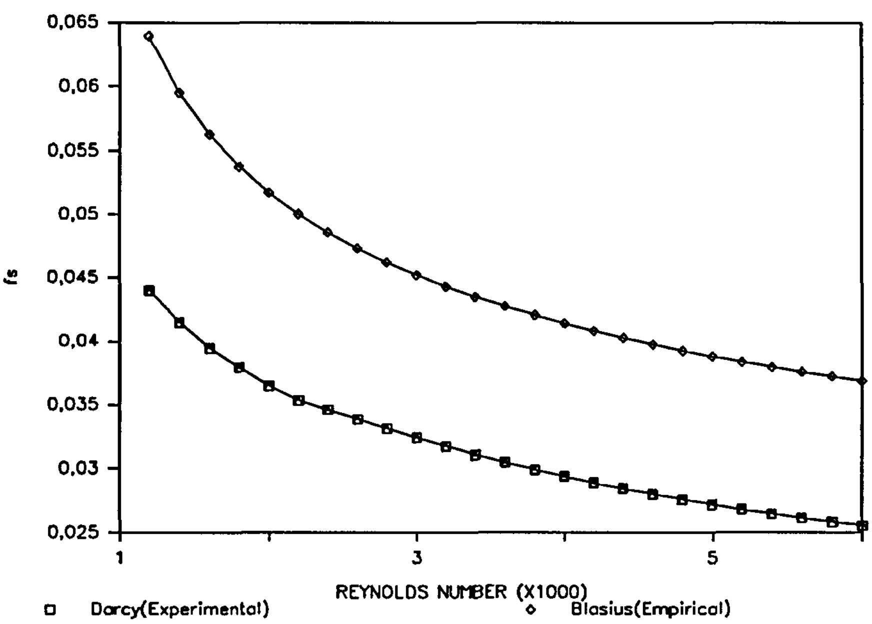
The empirical law of Blasius states that

$$f_s \;=\; 0{,}3164\,/\,Re^{1/4} \qquad (5)$$

in the range of 3 000 < Re < 10 000

The Stanton friction factor was determined from equation *(5)*, Blasius, and these f_s values were compared with those derived from the curves fitted to the experimental data (Figures 3.1 to 3.6) in combination with equation *(4)*. The two sets of f_s values are compared in Figure 3.9 which shows similar trends with varying Re-numbers. The f_s values determined with the aid of the Blasius relationship are consistently higher across the whole range of Re-numbers by an almost constant factor.

FIGURE 3.9 : COMPARISON OF FRICTION FACTORS DETERMINED BY DARCY AND BLASIUS EQUATIONS



In/outlet component (ΔP_{ends})

By subtracting the tube friction component, ΔP_{length} from the total pressure drop, ΔP_{tot} the in/outlet component, ΔP_{ends} is determined. Ideally, the experimentally determined tube friction component should be subtracted from the actual experimental values in order to eliminate the errors introduced by fitting curves to the data. However, the Re-numbers at which experimental pressure drops were measured, differed for the various modules and the fitted values had to be used to determine $\Delta P/\Delta L$. The mean values of the respective $\Delta P/\Delta L$ curves, given in Figures 3.7 and 3.8, were subtracted from the fitted total pressure drop values (Figures 3.1 to 3.6) and the results are shown in Figures 3.10 and 3.11. Using the Darcy and Blasius relationships, the simulated $\Delta P/\Delta L$ values may also be subtracted from the experimental pressure drop as shown in Figures 3.10 and 3.11. From these results the conclusion can be made that the in/outlet component, ΔP_{ends} can be ignored for practical purposes when simulating the pressure drop over a capillary module. This assumption does not take into consideration the pressure loss due to the difference between the feedpipe diameter and the inside diameter of the coupling piece.

FIGURE 3.10 : ΔP_{ends} COMPONENT FOR N100L325 MODULE

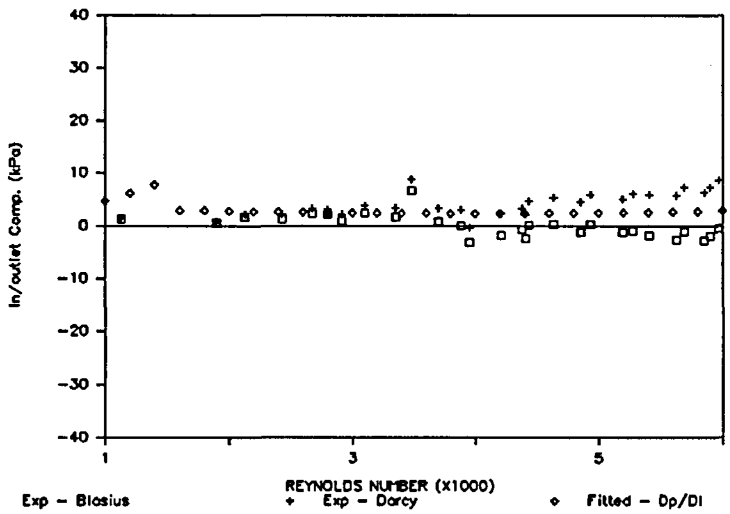
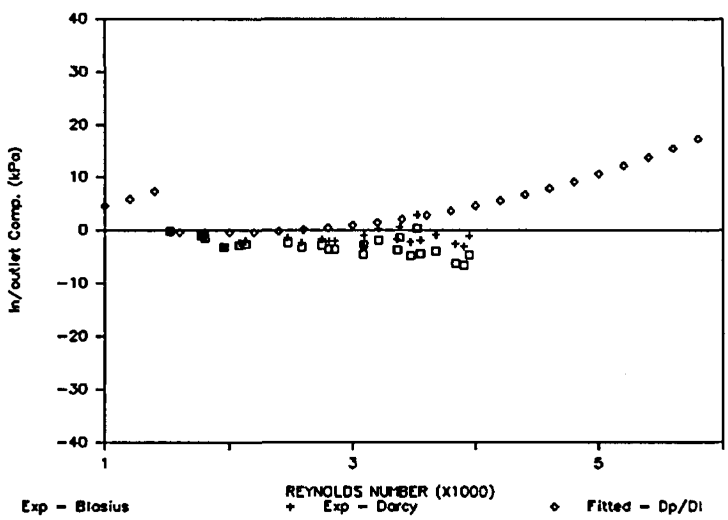


FIGURE 3.11 : ΔP_{ends} COMPONENT FOR N150L405 MODULE



3.1.3 CAPILLARY MODEL

Using either the experimentally determined f_s or the empirical f_s provided by Blasius with the Darcy equation, one can simulate the pressure drop due to tube friction through any capillary tube if the Re-number is known. Figures 3.12 to 3.17 show the accuracy of these simulations for the six capillary modules that were used in the experiment.

FIGURE 3.12 : COMPARISON OF EXPERIMENTAL AND SIMULATED PRESSURE DROP - MODULE N100L325

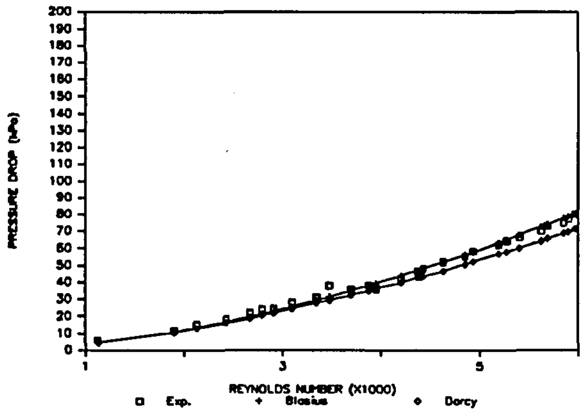


FIGURE 3.13 : COMPARISON OF EXPERIMENTAL AND SIMULATED PRESSURE DROP - MODULE N100L410

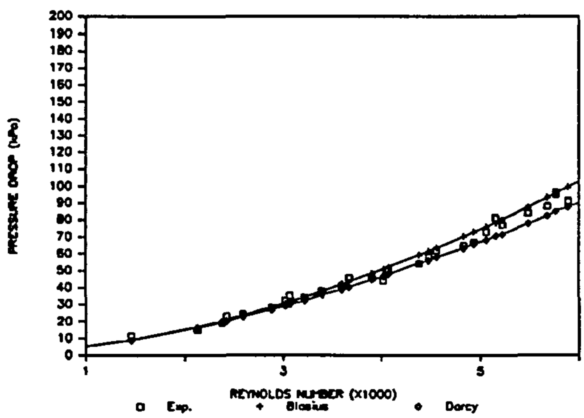


FIGURE 3.14 : COMPARISON OF EXPERIMENTAL AND SIMULATED PRESSURE DROP - MODULE N100L615

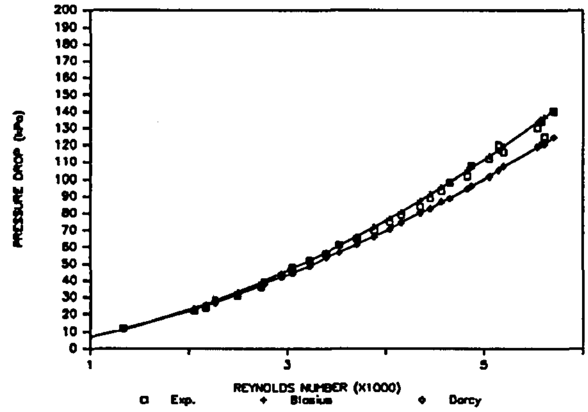


FIGURE 3.15 : COMPARISON OF EXPERIMENTAL AND SIMULATED PRESSURE DROP - MODULE N150L300

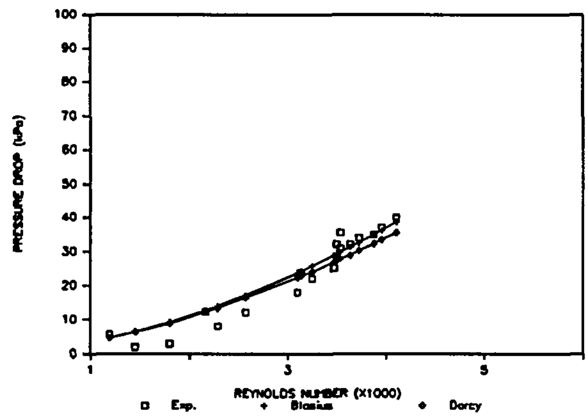


FIGURE 3.16 : COMPARISON OF EXPERIMENTAL AND SIMULATED PRESSURE DROP - MODULE N150L405

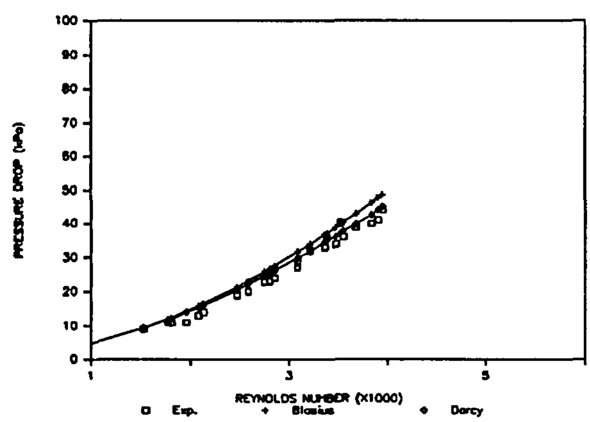
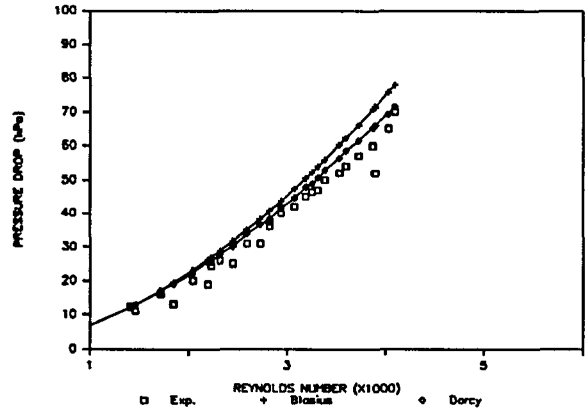


FIGURE 3.17 : COMPARISON OF EXPERIMENTAL AND SIMULATED PRESSURE DROP - MODULE N150L610



Figures 3.12 to 3.17 demonstrate that a good correlation is obtained between the actual experimentally determined pressure drop values and those predicted by the Darcy relationship given in equation *(2)*. The Stanton friction factor f_s, which is used in conjunction with the Darcy relationship, may be calculated from the empirical law of Blasius or by reading off the experimental f_s-Re curve in Figure 3.9.

The Darcy equation, in conjunction with the Blasius law for f_s, may therefore be used as a useful practical tool to predict hydraulic pressure drop across any capillary module.

3.2 APPLICATION : NATURAL WATER

The removal of colour from a natural water sample by ultrafiltration was investigated during a comparative test with capillary modules and standard tubular membranes. Colour in natural waters is caused by a variety of organic acids, primarily humic and fulvic type acids. These acids are formed naturally during the decomposition of organic matter and have molecular weights ranging from approximately 800 to as high as 50 000 *(Desal, 1991)*.

The presence of colour in natural water is not only objectionable from an aesthetic point of view, but may also lead to the formation of trihalomethane (THM) precursors. THM precursors are known to liberate chloroform and other halogenated hydrocarbons when the water is chlorinated during disinfection. Trihalomethanes have been shown to possess carcinogenic properties and the prevention of their formation is therefore of considerable importance in the supply of potable water.

3.2.1 FLUX VALUES

Ultrafiltration tests on the removal of colour from natural water were performed over a 30 day period according to the method described in paragraphs 2.1.2 and 2.2.2.

A prototype capillary module was operated in parallel with standard 12,5 mm ϕ tubular membrane samples of the 719 and 442 type. The tubular membrane samples were inserted in suitable test cells. Details about operating conditions and molecular mass cut-off (MMCO) ratings for each membrane type are given in Table 3.2.

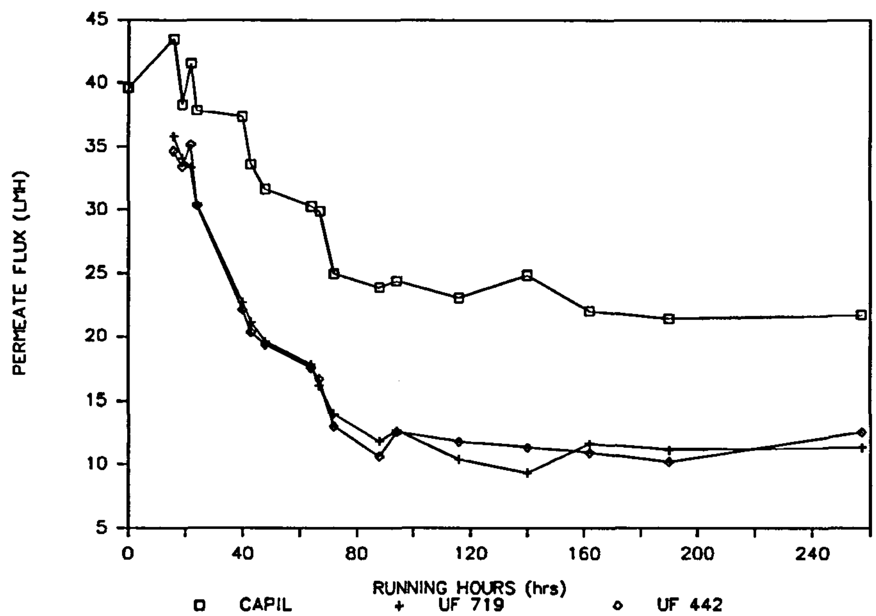
TABLE 3.2 : OPERATING CONDITIONS AND MEMBRANE PARTICULARS FOR COLOUR REMOVAL EXPERIMENTS

Parameter	UF 719	UF 442	Capillary
Inlet pressure (kPa)	400	400	200
Outlet pressure (kPa)	350	350	35
Linear flow velocity (m/s)	1,5	1,5	5,6
MMCO (dalton)	40 000	6 000	4 000
Membrane area (m^2)	0,12	0,12	0,30

Flux values for the first 260 hours of continuous operation are illustrated in Figure 3.18. It may be seen from this graph that a rapid, almost linear, flux decline occurred within the initial 80 hours after which the flux stabilised towards an asymptotic value in all three cases. The flux values of the two tubular membrane types proved to be similar although their MMCO and inherent pure water flux are known to be inherently different *(Strohwald and Jacobs, 1991)*. One would expect the flux of the higher cut-off 719 membrane to be higher than that of the 442 membrane. The phenomenon seen in Figure 3.18, however, is not unfamiliar and may be explained by the rapid build-up of a dynamic gel-layer on the surface of the high cut-off, high flux 719 membrane which in reality acts as a secondary membrane *(Strohwald and Jacobs, 1991)*.

Whereas the flux of the tubular membranes declined from approximately 35 to 12 LMH over the 260 hour period, those of the capillary membranes varied from about 40 to 22 LMH. The average stabilised flux values (between 80 and 260 hours) of the capillary module were higher by a factor of 2 when compared to the tubular membranes. This may be due to the higher flow velocity at which the capillary module was operated (refer Table 3.1), resulting in better control of the gel-layer thickness. Another contributing factor may be the different membrane surface topography and morphology found in these membranes.

FIGURE 3.18 : COMPARISON OF FLUX VALUES FOR DIFFERENT MEMBRANES - COLOUR REMOVAL FROM WATER

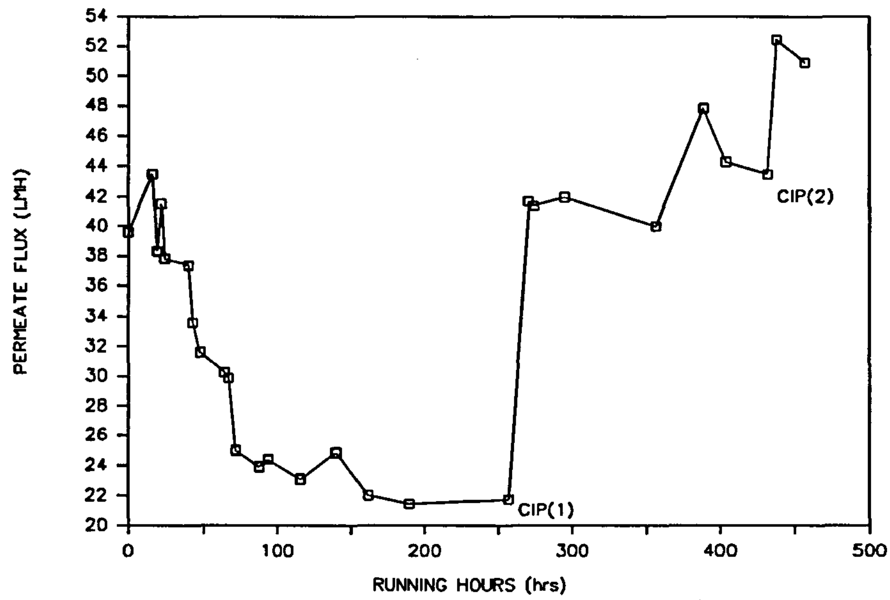


3.2.2 MEMBRANE FOULING AND FLUX RESTORATION

The flux decline illustrated in Figure 3.18 was attributed to membrane fouling by dissolved organic constituents. Membrane fouling and ultrafiltration are synonymous, in other words fouling is an integral part of the ultrafiltration process. Membrane fouling becomes problematic when the flux is affected to such a degree that the low productivity makes the process unfeasible. Unless the fouling is irreversible, membrane flux may generally be restored by chemical cleaning of the membrane. This is achieved by circulating a cleaning solution through the membranes and is referred to as a cleaning-in-place (CIP) procedure.

In this instance the flux of the capillary module could be restored to starting levels as illustrated in Figure 3.19. Two different cleaning solutions were used with success. CIP(1) entailed a 3% enzymatic proteolytic cleaner which had been employed previously, with promising results, on membranes treating abattoir wastewater *(Jacobs, 1991)*. A significant flux increase from 22 to 40 LMH was achieved. A second cleaning cycle, CIP(2), was performed at 435 hours which succeeded to further increase flux values from 44 to 52 LMH.

FIGURE 3.19 : RESTORATION OF CAPILLARY MODULE FLUX BY CIP - COLOUR REMOVAL FROM WATER

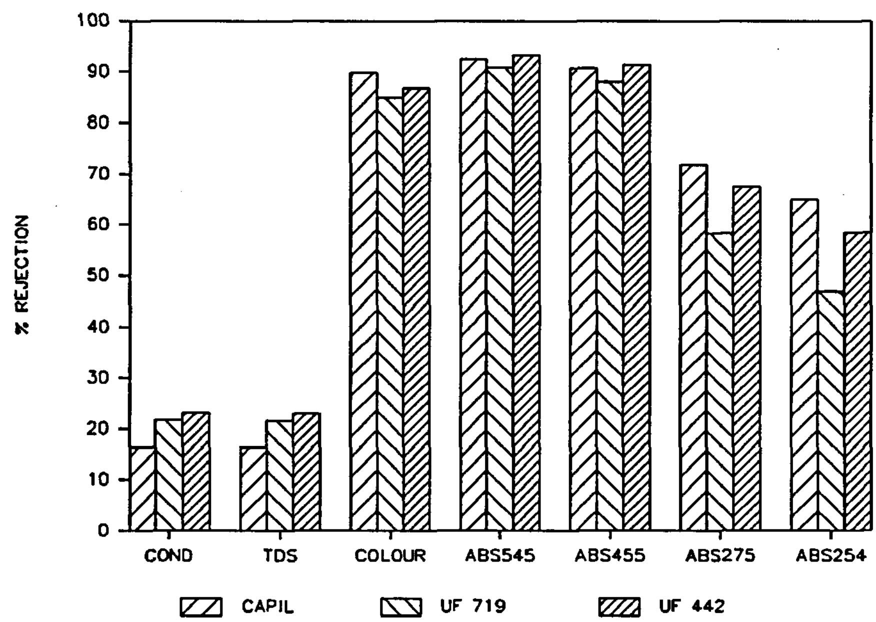


3.2.3 SEPARATION CHARACTERISTICS

Feedwater and permeate samples from the various membrane types were analysed with regard to conductivity, total dissolved solids (TDS), colour and absorbance at various wavelengths (545, 455, 275 and 254 nm). The percentage reduction of these parameters by the different membranes are presented graphically in Figure 3.20.

It follows from the above figure that similar reduction percentages were obtained with respect to all parameters that were analysed, regardless of the type of membrane. This may be expected from the capillary and UF 442 membranes because of their virtually identical MMCO (4 000 and 6 000 dalton respectively). Surprisingly, however, the UF 719 membrane with a designated MMCO of 40 000 dalton produced the best colour and absorbance reductions. Again, this is attributed to the formation of a significant dynamic gel-layer on the membrane surface which affects the separation characteristics. It would seem from the similar separation characteristics obtained with membranes of dissimilar MMCO (UF 719 and capillary) that the higher flux obtained with the capillary membranes may well be the result of higher flow velocity, as was postulated previously.

FIGURE 3.20 : COMPARISON OF PERMEATE QUALITIES - COLOUR REMOVAL FROM WATER



3.3 APPLICATION : SEAWATER

In the desalination of seawater by reverse osmosis (RO) the correct pretreatment of the feedwater is often of cardinal importance to ensure sustained high performance of the RO membranes. This is even more critical in highly efficient desalinators such as hollow fine-fibre systems. One of the pretreatment options that will produce a RO feedwater of consistently high quality, irrespective of variations in raw seawater quality, is the use of ultrafiltration *(Strohwald, 1992).*

The capital cost of conventional ultrafiltration systems, used in the production of ultra-pure water and in food applications, is generally too high to make the pretreatment of seawater by UF a viable proposition. A research project for the development of a locally manufactured, low-cost ultrafiltration system was therefore launched to overcome this problem *(Strohwald et.al., 1993).* A prototype capillary module was evaluated in the course of this work, together with other membrane configurations. Some of the initial module performance results, with specific reference to the capillary configuration, are presented here.

3.3.1 FLUX VALUES

The different module types were evaluated and operated according to the procedures described in paragraphs 2.1.2 and 2.2.2 as well as Table 2.1.

Flux values for three different module types, viz. capillary, MEMTUF and SWUF, were logged over a period of 1 600 hours as depicted in Figure 3.21. It may be seen from this graph that a rapid flux decline was experienced with all module types within the first 80 hours of continuous operation from as high as 90 to around 10 LMH for both the MEMTUF 719 and SWUF 719 modules. The start-up flux for the capillary module, on the other hand, was considerably lower at 26 LMH and also reduced to approximately 10 LMH during this period.

3.3.2 MEMBRANE FOULING AND FLUX RESTORATION

Several CIP cycles were performed on site (refer to Table 3.3) which failed to significantly raise the flux values of the MEMTUF 719 and SWUF 719 modules. In case of the capillary module considerable success was achieved with CIP(4) and CIP(5) which served to restore seawater flux values to close to the start-up flux of 26 LMH. Subsequent, consecutive CIP's (6), (7) and (8) achieved complete flux restoration and also resulted in sustained higher flux. This may be explained by the possible modification of membrane morphology due to contact with chlorine *(Strohwald and Jacobs, 1991)*.

The seawater flux of the capillary and MEMTUF 719 modules stabilised at 20 and 16 LMH, respectively for the remainder of the test period.

FIGURE 3.21 : COMPARISON OF FLUX VALUES FOR DIFFERENT MEMBRANES - FILTRATION OF SEAWATER

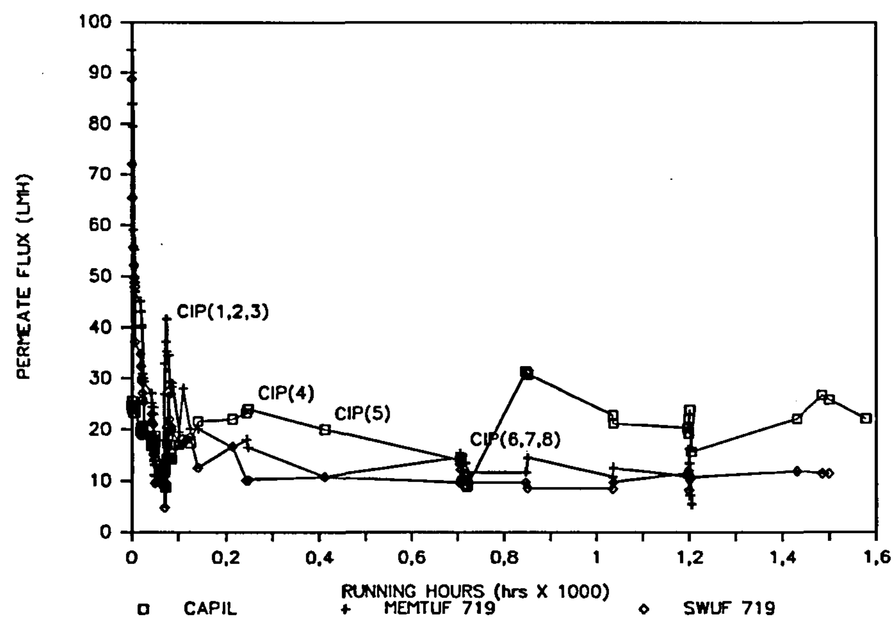


TABLE 3.3 : DETAILS OF ON-SITE CIP - SEAWATER

CIP	Type	Hours
1	Biotex (1% 60 minutes)	72
2	HCl (pH 2)	73
3	EDTA (0,5% pH 8)	74
4	HCl (pH 2)	246
5	HCl (pH 1,5)	411
6	H_2SO_4 (pH 1,5)	705
7	CaOCl 200 ppm (NaOH to pH 10)	706
8	HCl (pH 1,5)	707

SECTION FOUR : CONCLUSIONS AND RECOMMENDATIONS

4.1 CONCLUSIONS

4.1.1 HYDRODYNAMICS

Comparison of the experimentally determined pressure drop data with semi-empirically and empirically determined Stanton friction factors, f_s showed that the total pressure drop across the prototype capillary modules may be estimated by the Darcy equation. The pressure losses due to in-/outlet effects were found to be negligible for practical purposes. As such the empirical Blasius relationship, for the calculation of f_s, together with the Darcy equation for friction losses may be used as a practical tool to predict pressure drop across the prototype capillary modules at a specific Re-number.

4.1.2 APPLICATIONS

The use of prototype capillary modules in the removal of colour from natural water and the filtration of seawater proved that similar productivity and degrees of separation to commercially manufactured tubular modules may be obtained.

Some of the advantages of the capillary modules are the following:

(i) Due to the parallel configuration of the capillaries the pressure drop across the capillary bundle is considerably less than that of a series configured tubular module of similar membrane area. It is therefore possible to operate the capillary modules at higher linear flow velocity (or Re-numbers) for increased turbulence. This in turn results in better control of the dynamic gel-layer thickness with resultant higher flux.

(ii) The high packing density (ratio of membrane area per volume) together with low cost of construction make this configuration a potential candidate for the clarification of a variety of feedwaters.

(iii) Membrane productivity may be increased and fouling may be controlled by adopting higher than normal flow velocities (when compared to series configured tubular modules) and standard chemical cleaning methods.

The requirement of increased pretreatment with regard to suspended solids (to prevent physical blockage of the capillaries) may be considered as a possible disadvantage. This, however, is easily overcome by inexpensive, conventional filtration techniques.

4.1.3 GENERAL

The work described in this report is regarded as a basis for the characterisation and evaluation of prototype capillary modules. The intention is to use these results for the preparation of specifications which will fix the construction parameters of the first commercially manufactured model.

The initial project objectives may, therefore, be considered to have been satisfied.

4.2 RECOMMENDATIONS

Future work on this subject should concentrate on the finalisation of specifications for a commercially manufactured production model. This should be followed by the construction of such capillary modules with subsequent use of the products in selected industrial applications.

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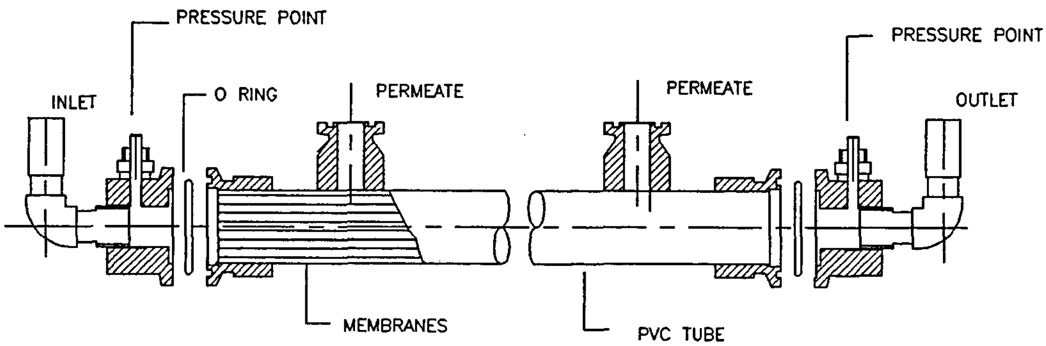
FIGURE 2.1 : SCHEMATIC DIAGRAM OF CAPILLARY MODULE



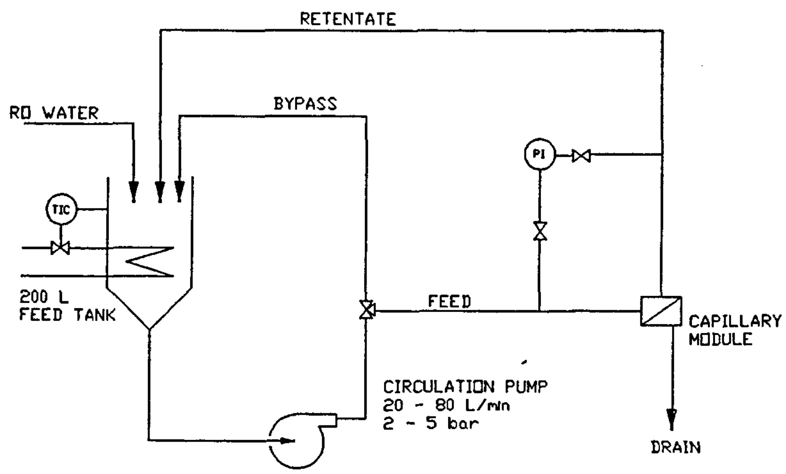
Test Bench

The capillary test system, schematically depicted in Figure 2.2, comprised a batch tank, feed pump and prototype capillary modules. RO water produced from municipal supply, was used as medium in the experimental runs to minimise variations in viscosity and physical characteristics between different runs. The temperature of the water in the 200 l feed tank was controlled by a temperature controller acting on a solenoid valve in the cooling water circuit. A master gauge with an accuracy of 0,5% was used to measure the pressure at the inlet and outlet of the modules in the higher pressure ranges. A mercury manometer was used in the lower pressure ranges to reduce experimental error. The linear flow velocity in the capillaries was varied by adjusting the by-pass valve on the discharge side of the circulation pump.

2.1.2 APPLICATION : NATURAL WATER

The ultrafiltration system used in colour removal experiments consisted of a feed tank, transfer pump, buffer tank, circulation pump and UF capillary module (refer Figure 2.3). The water level in the buffer tank was maintained with water supplied from the feed tank by the transfer pump . The temperature of the feedwater to the capillary module was controlled by circulating tap water through a cooling coil in the feed tank. The recovery of the system was controlled by feeding and bleeding in the required proportions. Pressure gauges on the in- and outlet sides of the capillary module indicated the operating pressure and pressure drop across the module.

FIGURE 2.2 : LINE DIAGRAM OF EXPERIMENTAL EQUIPMENT USED FOR DETERMINATION OF CAPILLARY MODULE HYDRODYNAMICS



2.1.3 APPLICATION : SEAWATER

Capillary modules used in the experiment had membranes with typical external and internal diameters of 1,8 and 1,5 mm respectively. Bundles of 200 to 250 capillaries were housed in clear uPVC tubes to give an overall module length of 1 m. The internally-skinned membranes were end-potted in a tube-and-shell arrangement with a special epoxy which adheres well to PVC.

The 719-series UF membranes used in the MEMTUF modules had a molecular mass cut-off (MMCO) of 40 000 dalton while two types were used in the SWUF modules, a similar 719-series 40 000 MMCO membrane and a 442-series membrane of 6 000 MMCO. The membranes of the capillary modules had an effective MMCO of 4 000 when tested on an aqueous solution of PEG.

The various membrane systems were skid-mounted to allow simultaneous evaluation of the different configurations. The test equipment was installed on a jetty of West Point Fishing Co. where seawater could be obtained from existing intake piping. The raw seawater was first screened to 300 μm before being subjected to dual-media filtration. Filtered seawater was collected in a 200 l buffer tank from which it was distributed to the various modules by means of a centrifugal pump and ring manifold. Take-off points for the individual modules were provided with pressure gauges for the determination of operating pressure. The mechanical line diagram for the experimental skid is illustrated in Figure

2.4. A second 200 μm screen was installed ahead of the capillary module to prevent physical blocking of the capillaries by solids (e.g. carry-over grit from the sand-filter).

FIGURE 2.3 : SCHEMATIC OF EXPERIMENTAL EQUIPMENT USED IN COLOUR REMOVAL FROM WATER

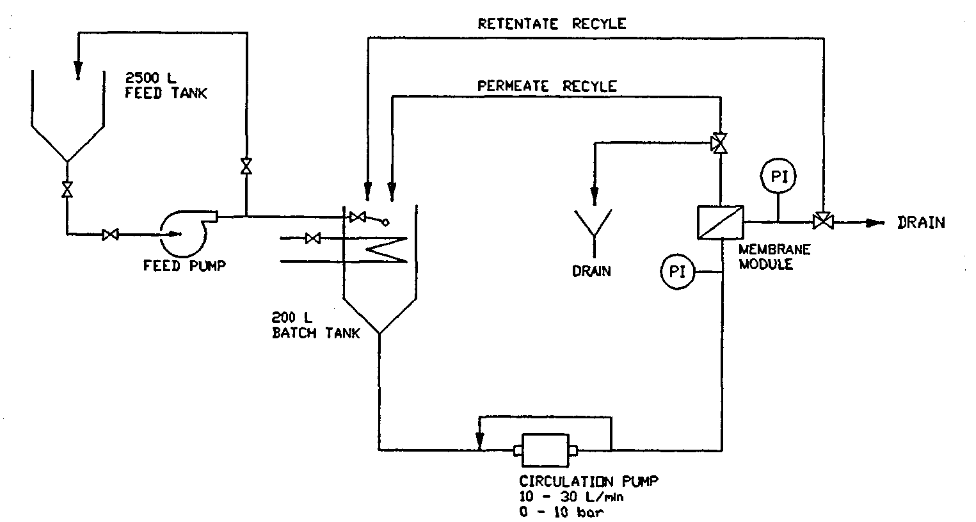


FIGURE 2.4 : SCHEMATIC OF EXPERIMENTAL EQUIPMENT USED FOR FILTRATION OF SEAWATER