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Screw-thread flow promoters: an experimental study of ultrafiltration and microfiltration performance

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Abstract

The screw-thread flow promoters presented in this work are designed to enhance filtration in a tubular geometry using a standard half-inch diameter. Two separate experimental studies were undertaken to evaluate the ultrafiltration of BSA and the microfiltration of bovine blood.

The convective mixing in each system was augmented through a combination of two vortex patterns: helical flow around a semi-circular cross section and flow through a sudden expansion. The screw-threads are simple to construct and operate well under laminar, quasi-steady flow conditions such that scale-up and the processing of shear sensitive fluids should be possible.

The internal screw-thread generated 75% of the clean water flux at a high BSA concentration of 60 g/l. The superposition of an oscillatory flow component on the mean flow did not significantly improve the performance. The internal screw-thread design performed poorly when applied to the separation of plasma from whole blood because the centrifugal forces appeared to complement concentration polarization. An external screw-thread design was found to be an effective anti-fouling technique and tripled the microfiltration performance relative to an internal screw-thread. The lower pitch of 3.5 mm gave a plasma flux of order 0.1 cm/min, moderate flux decline and no signs of haemolysis.

Keywords: Screw-thread; Ultrafiltration; Microfiltration; Laminar flow

1. Introduction

A growing number of biochemical and biomedical processes employ passive membranes for key separation tasks. The applications range from the microfiltration of biological fluids to the ultrafiltration of food and beverages. The university-based research into the various aspects of membrane filtration has tended to produce bench-top scale systems which employ novel methods for flux enhancement, such as electrofiltration, baffles and backflushing. The aim is to inhibit the build-up of suspended or dissolved material on the membrane surface because concentration polarisation plays an important role in flux limitation [1]. In the transition to commercial scale systems the complexity of bench-top scale systems is generally sacrificed in favour of traditional, high flow rate devices that operate in the turbulent regime. These require powerful, expensive pumping systems, and difficulties can arise when processing delicate fluids such as mammalian cells.

We wish to design membrane systems which can process a wide range of shear-sensitive fluids, and this generally means operating in the laminar flow regime.

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Flux enhancement and flux control under laminar flow conditions can be achieved by generating well-defined secondary-flow structures. A stable, uniform vortex pattern can be used to mix the fluid phase and "wash" the membrane surface, but for efficient global mixing the region of recirculating flow needs to be mixed with the main feed flow. It is not always possible to achieve this within the laminar flow regime. If we take the case of flow in a tubular geometry then the use of circumferential fins can, in some circumstances, decrease convective transport due to flow distortion [2]. The use of baffles to enhance microfiltration has only been successful when the radial velocities are high, which leads to high Reynolds numbers and the flow becomes turbulent [3]. Membrane performance can be enhanced at low Reynolds numbers if there is some form of external agitation to the flow circuit. This can take the form of pulsatile flow [4] or oscillatory flow in a partially obstructed channel [5].

One method that generates a stable, regular pattern of vortices in an annular gap is Taylor–Couette flow. The fluid dynamics and transport properties were established several decades ago and the technique has been used to augment many filtration processes [6] together with blood oxygenation [7], catalytic reactors [8], and liquid–liquid extraction [9]. The advantage of Taylor–Couette flow is that the residence time distribution can be independent of the wall shear rate, but in terms of filtration modules, the rotary systems have only been successful in the high-value, small-scale biotechnology environment.

In an attempt to overcome the scale-up limitations of the Taylor–Couette systems, recent reports have employed Dean vortices to depolarize solute build-up for Poiseuille flow through curved channels [10,11]. The vortices are formed due to centrifugal instabilities, and in order to maintain the vortices, and hence maintain the flux, the channel curvature needs to increase with channel length. This generates a complex spiral geometry.

The main focus of the work carried out in Oxford has been the design of efficient, uncomplicated membrane modules that do not rely on external flow features, so that scale-up is a viable option. The method we have employed to generate secondary flows is based on screw-thread flow promoters applied internally and externally to a tubular membrane geometry. The rationale behind this method is that vortices can be generated from a sudden flow expansion or due to centrifugal instabilities. The screw-thread flow promoters combine both of these features in order to generate effective mixing. The screw-thread flow promoters produce a continuous spiral of vortices on the inner or outer surface of a tubular membrane; consequently, the flow field is similar in nature to a Taylor–Couette system. Previous studies have examined internal [12] and external [13] helices, but our methods differ because we augment the rotary fluid flow with a leakage flow over a screw-thread of low pitch.

This paper will highlight some of the fundamental differences between ultrafiltration and microfiltration as the fluid phase in each system is apparently subjected to the same hydrodynamic environment. The screw-thread flow promoters were initially applied as inserts to ultrafiltration and microfiltration membranes, and the design of the screw-thread flow promoters was adapted to tackle the problematic area of microfiltration. The ultrafiltration performance was assessed with high concentrations of bovine serum albumin (BSA). The microfiltration experiments focused on the separation of plasma from whole bovine blood. Blood is a viscous, shear sensitive fluid and provides an excellent challenge to any microfiltration system.

2. Materials and methods

2.1. Ultrafiltration

The ultrafiltration rig was built with two PCI tubular membranes (PCI Membrane Systems Ltd., polysulfone PU 120 with molecular weight cut-off of 20 kDa) arranged in a U-shaped path. Each tubular membrane was of internal diameter 12.5 mm and effective length 950 mm. This gives a total membrane area of 74.6×10^3 mm^2.

The geometry of the internal screw-thread flow promoter is shown in Fig. 1. A crucial feature of the screw-thread design is that the secondary flow structure is generated through a combination of both helical flow following the screw-thread and leakage flow through the sudden channel expansions. The helical flow path has a semi-circular cross-section and the pitch can be set at 3.5 or 5.5 mm, which gives a cross-section of radius $a = 1.5$ mm and $a = 2.5$ mm, respectively. If we define the radius of curvature about the central axis of

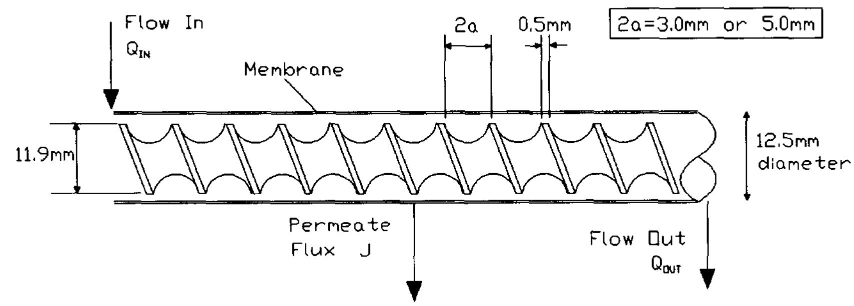

Fig. 1. Cross-section of the internal screw-thread showing the semi-circular, helical flow path.

the screw-thread as $r=5.95$ mm (see Fig. 1) and rewrite the pitch as $2\pi b$ then we can classify the screw-thread in terms of two non-dimensional numbers: the curvature κ and the torsion τ. The curvature and torsion are given by

$$\kappa=\frac{ra}{b^2+r^2} \quad \tau=\frac{ba}{b^2+r^2} \tag{1}$$

The internal screw-thread with a 5.5 mm pitch has a curvature of $\kappa=0.41$ and a torsion of $\tau=0.06$.

A prominent dynamic feature of flow in a curved channel or helical pipe is the generation of secondary flows resulting mainly from the interplays between pressure gradient, centrifugal acceleration and viscous effects. The characteristic feature of flow in a toroidal pipe ($\tau=0$) is the formation of a pair of counter-rotating vortices, provided the Dean number is above some critical value. The Dean number is a function of the Reynolds number and the curvature, and defined as $De=Re^2\kappa$ [14]. Flow in a helical pipe differs from that in a toroidal pipe in that the vortex structure becomes asymmetric. A number of studies have shown that laminar flow [$Re=O(100)$] in a helical pipe [$\kappa=O(0.1)$ and $\tau=O(0.01–0.1)$] generates significant secondary flow patterns [14–17]. As a general rule, an increase in the curvature κ will increase the strength of the vortex pattern, and an increase in the torsion τ will change the orientation and relative magnitude of the vortices. Although the cross-section of the screw-thread inserts used in this study are semi-circular rather than the circular cross-section found in most of the literature, we are confident a secondary flow structure will be produced at moderate flow rates because multiple vortex patterns have been observed in other non-circular helical geometries [18].

The helical vortex structure is further augmented by the leakage flow. The leakage flow through the minimum gap of 0.3 mm encounters a form of backward-facing step (expansion ratio of approximately 8) which would form a single vortex due to the adverse pressure gradient. The zone of recirculation within the semi-circular cross-section of the screw-thread is inherently three-dimensional, and a theoretical interpretation of the complex flow structure is beyond the scope of this paper.

The ultrafiltration experiments reported in this work were performed with an internal screw-thread with a pitch of 5.5 mm. The tubular membrane system was also run with a uniform rod insert of 9.9 mm diameter in order that the performance of the screw-thread flow promoter could be compared with a standard module design. The concentration of BSA in the up-stream reservoir was fixed at approximately 60 g/l and the protein-free flux through the membrane for both types of insert was measured under a range of hydrodynamic conditions.

A double roller, peristaltic pump (Sarns Inc, Ann Arbor, MI, USA, model 5500) was used to provide quasi-steady flow through the flow circuit (Fig. 2). The compression ratio on the 6 mm bore pump tubing (tubing bore divided by minimum gap) was set at approximately 3. At this level of constriction the shear was considered to be low enough to avoid denaturing the protein. Incorporated into the flow circuit was an oscillatory flow generator. This comprised of a pair of circular, flexible pump bags at the inlet and outlet of the U-shaped tubular channel. Oscillatory flow was generated by a pair of circular pistons (area 314 mm^2) driven in anti-phase, through a motor and swash plate, at a stroke length of 7mm and a frequency of 4 Hz. This gave a peak oscillatory flow rate of 1657 ml/min, which is an order of magnitude greater than the mean flow through the system.

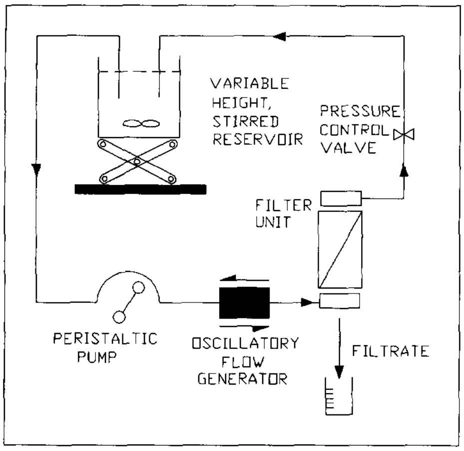

Fig. 2. Schematic representation of the filtration circuit.

The permeate flow rate was measured over a 1 min period, and then recycled to the reservoir such that the concentration of BSA remained constant. The flow rate at inlet Q and the filtrate flow rate P were each measured twice for each flow condition. The trans-membrane pressure was maintained at 2.0 bar for all experiments by varying a needle valve in the outlet line. The pressure at the inlet and outlet of the ultrafilter was measured with a Budenberg gauge. The filtrate was collected at atmospheric pressure.

Fresh bovine serum albumin was mixed with distilled water to a concentration of 60 g/l and the mean value of the pH was found to be 6.99. At the start of each experiment the circuit was primed with distilled water, and the clean water flux at a trans-membrane pressure of 2.0 bar was measured. The measurement of clean water flux was repeated at the end of each experiment. The BSA solution was pumped from the 750 ml reservoir until 300 ml of prime water was displaced. The prime volume of the circuit, excluding the reservoir, was measured at 400 ml; thus the true concentration of the BSA solution was 52.9 g/l.

2.2. Microfiltration

Microfiltration is more problematic but also potentially more profitable than ultrafiltration [19]; consequently, the design of the membrane modules needed to be adapted in order to enhance microfiltration fluxes. Initial experiments with internal screw-threads did not produce significant improvement over a uniform rod insert. The centrifugal acceleration generated with the rotary, helical flow was thought to throw the blood cells onto the inner surface of the tubular membrane, hence increasing the rate of concentration polarization. In order to reduce this particulate layer the centrifugal forces were harnessed in the form of an *external* screw-thread flow promoter.

The design of the internal screw-thread was exactly the same as that used in the ultrafiltration experiments (Fig. 1). The pitch could be set at 3.5 or 5.5 mm and the minimum gap was constant at 0.3 mm. The microfiltration membrane unit had a diameter of 12.5 mm and a length of 200 mm, to give an active membrane area of 7900 mm^2. The tubular membrane was fabricated from flat sheets of microfiltration membrane, and the cylindrical structure was maintained using a combination of heat sealing and gluing. The membranes were supported by a rigid Perspex shell with longitudinal plasma collection channels machined into it.

Two types of microfiltration membrane were tested: (1) Supor, a polyethersulfone membrane with a nominal pore size of 0.2 μm; and (2) Versapor, an acrylic co-polymer membrane with a nominal pore size of 0.45 μm (both manufactured by Gelman Sciences, UK). The manufacturer describes each as a homogeneous microporous membrane, but the Versapor is cast on a non-woven nylon substrate which provides strength and rigidity. A full description of the membrane morphology has been provided by Tartleton and Wakeman [20].

The design of the external screw-thread flow promoter is shown in Fig. 3. The tubular microfiltration membrane (length 200 mm and area 7900 mm^2) was supported on a grooved cylindrical core, and the membrane was fixed in position on the inside of the screw-thread. The helical flow path was provided by a moulded epoxy shell. It should be noted that, in both the internal and external screw-thread designs, the feed flow enters the membrane unit at right angles to the axis of the membrane channel in order that the tangential velocity components are reasonably high at inlet. The external screw-thread contained some design features identical to the internal variant: the cross section was semi-circular, the pitch could be set at 3.5 or 5.5 mm, and the minimum gap was 0.3 mm. A summary of the curvatures and torsion used in this study, with internal and external screw-threads, is given in Table 1.

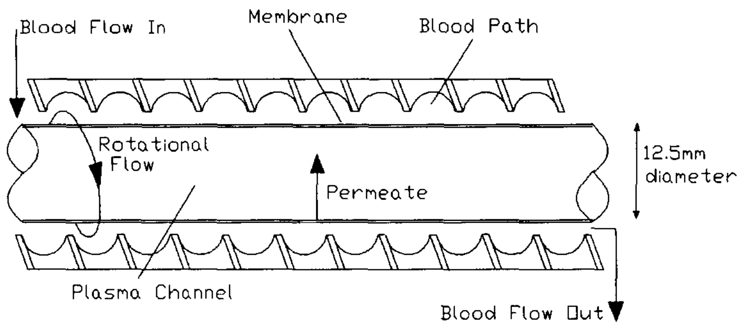

Fig. 3. Cross-section of the external screw-thread. The semi-circular flow path, pitch settings and minimum gap are the same as the internal screw-tread. The inner, grooved core which collects the plasma is not shown.

Experiments were carried out on fresh bovine blood, anticoagulated with citrate phosphate dextrose (CPD). The flow circuit was similar in nature to that used in the ultrafiltration experiments (see Fig. 2) the main differences being that no oscillatory flow generator was used and no pressure control valve was required. The pressure at outlet was set by the height of the blood reservoir in the range 0.07 to 0.09 bar. The pressure at outlet was measured with a mercury manometer, and the pressure at inlet was measured with a Budenberg gauge. The filtrate was collected at atmospheric pressure. Blood was driven from a 1000 ml reservoir by a four-roller peristaltic pump (Watson-Marlowe Ltd., UK, model 505Di) to provide a mean flow in the range $Q=100$ to 400 ml/min. The plasma flow rate was measured with a cylinder and stopwatch and then recycled back to the reservoir such that the blood haematocrit was maintained at $H=38\%$.

Prior to each set of experiments the system was primed with saline in order to wet the hydrophilic membranes. The saline was then displaced with fresh blood. At a given blood flow rate, the microfilter was run for a 5-min period before a representative plasma flow rate was measured. All experiments were run at room temperature.

Table 1
Curvature and torsion values for both designs of screw-thread

	Internal: $r=5.95$ mm		External: $r=6.55$ mm	
	2π-$b=3.5$mm	2π-$b=5.5$mm	2π-$b=3.5$mm	2π-$b=5.5$mm
Curvature κ	0.25	0.41	0.23	0.38
Torsion τ	0.02	0.06	0.02	0.05

3. Results

3.1. Ultrafiltration

The performance of the screw-thread insert relative to a uniform rod insert can be assessed using the results listed in Table 2. The permeate flow rate from the high-concentration BSA solution was measured using quasi-steady flow (peristaltic pump only) and oscillatory flow (peristaltic pump and oscillatory flow generator). The values of flow rate Q listed in the second column refer to the average flow rate at inlet, and the permeate flow rate P is listed in the third column. The clean water flow rates were measured using the peristaltic pump only.

The results are presented in terms of total resistance R_T (units of bar min/cm), fluid-side resistance R_F and a ratio of membrane resistance to total resistance, R_M/R_T. The total resistance is the sum of the fluid-side resistance and membrane resistance:

$$R_T=R_F+R_M=\frac{\text{TMP}}{J} \quad (2)$$

The trans-membrane pressure remained constant at TMP = 2.0 bar for all experiments, and the filtrate flux J is the filtrate flow rate per unit membrane area (in units of cm/min). The membrane resistance can be calculated directly from the clean water flux:

$$R_M=\frac{\text{TMP}}{J_{\text{clean}}} \quad (3)$$

A measure of efficiency under the various flow conditions is given by the ratio of fluxes (BSA to clean water), which is also equal to the ratio of membrane resistance to total resistance: R_M/R_T. The analysis in

Table 2
Tubular ultrafiltration results comparing the performance of an internal screw-thread relative to a bare rod insert. The experiments ran for approximately 60 min. All measurements were made at TMP = 2.0 bar

Operating conditions	Rod insert: 9.9 mm diameter				
	Q (ml/min)	P (ml/min)	R_T (bar min/cm)	R_F (bar min/cm)	R_M/R_T
BSA (60 g/l)					
Oscillatory, low	144	15	99.47	68.38	0.31
Oscillatory, high	405	17	87.77	56.68	0.35
Steady, low	159	10	149.20	118.12	0.21
Steady, high	399	14	106.57	75.48	0.29
Clean water					
Beginning	384	48	31.08		1.00
End	366	46	32.43		0.96
Operating conditions	Screw-thread insert: 5.5 mm pitch				
	Q (ml/min)	P (ml/min)	R_T (bar min/cm)	R_F (bar min/cm)	R_M/R_T
BSA (60 g/l)					
Oscillatory, low	132	44	33.92	9.05	0.73
Oscillatory, high	379	45	33.15	8.28	0.75
Steady, low	148	32	46.63	21.77	0.53
Steady, high	375	44	33.92	9.05	0.73
Clean water					
Beginning	368	60	24.87		1.00
End	391	55	27.13		0.92

this section is based on the assumption that the fluid viscosity remained constant during the experiments.

The performance of the two types of insert can be judged in terms of the efficiency. The uniform rod insert performed best under oscillatory flow conditions with a high mean flow rate of $Q = 405$ ml/min but could only achieve 35% of the clean water flux. The screw-thread insert doubled the efficiency of the uniform rod insert for both steady and oscillatory flow. The addition of oscillatory flow did not significantly improve the efficiency of the screw-thread flow promoter or the uniform rod at the lower flow rate. The most striking result is that steady flow through the screw-thread filter provided 53% (low flow rate) and 73% (high flow rate) of the flux rate achieved with clean water at the same trans-membrane pressure.

There was no evidence of protein denaturing during the ultrafiltration experiments. The clean water flux did not change significantly for either the screw-thread or the rod insert, and the colour of the reservoir did not darken over the course of each experiment.

The advantage of presenting the results in terms of membrane resistance and fluid-side resistance is that the results in this study can be compared with other published data on ultrafiltration. One area of particular interest in Oxford has been using the vortex wave technique to enhance membrane performance. Bellhouse et al. [5] applied oscillatory flow through a flat channel containing a series of flow deflectors, and achieved a flux of $J = 0.066$ cm/min (TMP = 1.0 bar and BSA at 60g/l). The clean water flux at TMP = 1.0 bar was measured at $J_{clean} = 0.126$ cm/min. This translates to a membrane resistance of $R_M = 7.93$ bar min/cm and a fluid-side resistance of $R_F = 7.22$ bar min/cm. Using a high flow rate of $Q = 375$ ml/min through the screw-thread filter, we have achieved a fluid-side resistance of $R_F = 9.05$ bar min/cm which is of the same order as that from the vortex wave system. The advantages of the screw-thread flow system over the vortex wave design is that it is simple to construct, does not rely on oscillatory flow, and scale-up is feasible.

3.2. Microfiltration

The plasma flux (flow rate per unit membrane area) for a range of blood flow rates has been characterised

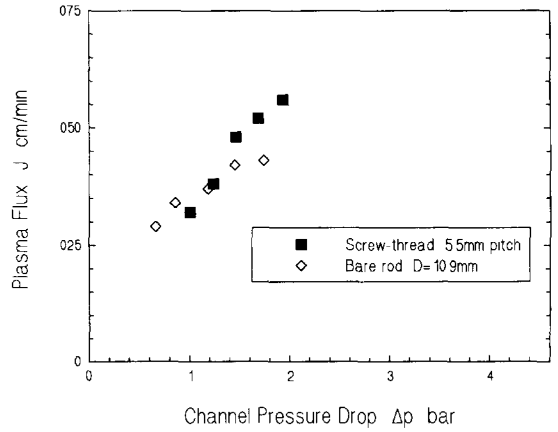

Fig. 4. Plasma flux versus channel pressure drop. The performance of an internal 5.5 mm pitch screw-thread is compared with a rod insert using Supor 0.2 μm membrane.

in terms of channel pressure drop. During ultrafiltration the trans-membrane pressure is of the order of 1 to 2 bar but microfiltration must operate at much lower trans-membrane pressures in order to avoid haemolysis [4], and consequently the channel pressure drop is the limiting feature of microfiltration devices. It should be noted that the channel pressure drops quoted in this section represent the sum of the pressure drops in the inlet, membrane and outlet regions.

The performance of an internal screw-thread with a pitch of 5.5 mm was compared with a uniform bare rod insert using the Supor 0.2 μm membrane. A rod insert of 10.9 mm diameter gave a similar pressure drop profile as the screw-thread insert, and this is shown in Fig. 4. Each insert was subjected to five inlet blood flow rates: $Q = 200$ to 400 ml/min in increments of 50 ml/min. The Watson-Marlowe pump allowed precise control of the inlet flow rates. At each blood flow rate the inlet pressure and outlet pressure were recorded so that the results could be plotted as plasma flux against pressure drop (Fig. 4). The performance of the screw-thread insert is very similar to the uniform rod insert, and the improvement in flux at an equivalent pressure drop is negligible.

The performance of the screw-thread designs was investigated further using the more rigid Versapor 0.45 μm membrane. In Fig. 5 the results for three designs are shown: (1) internal 5.5 mm pitch, (2) internal 3.5 mm pitch, and (3) external 5.5 mm pitch. The error bars represent maximum experimental error based on two separate experiments for each screw-thread design. Experiments were duplicated to compensate for the absence of temperature control within the stirred reservoir. The first data point for each screw-thread was recorded at an inlet flow rate of $Q = 150$ ml/min and each subsequent point represents an increment in the flow rate of 25 ml/min.

If we compare Fig. 4 with Fig. 5 we can see that a change in membrane pore size from 0.2 to 0.45 μm does not significantly affect the flux in relation to the channel pressure drop for the internal 5.5 mm pitch screw-thread. This suggests that the dominant flux resistance is that associated with the concentration boundary layer at the membrane surface. The 3.5 mm internal screw-thread gives a very similar set of results to the 5.5 mm internal pitch. A change in pitch from 5.5 to 3.5 mm significantly changes the curvature, torsion and helical path length, but this does not alter the flux pattern. It would appear that the internal helical flow pattern does not inhibit concentration polarization, and the centrifugal forces on the red blood cells may promote a particulate build-up on the membrane surface. The common set of results with the 5.5 and 3.5 mm pitch internal screw-threads indicates that the flux is controlled by the high-shear leakage flow through the 0.3 mm minimum gap rather than the helical flow structure.

There is a marked change in performance when an external 5.5 mm pitch screw-thread is employed. We observe that the pressure drop is increased but, somewhat surprisingly, the plasma flux is reduced in comparison to the internal screw-thread designs. Holdich

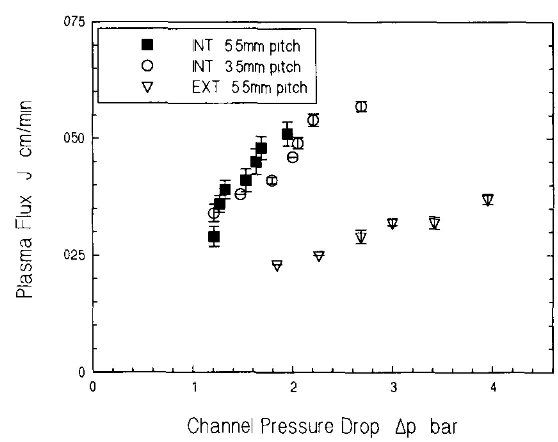

Fig. 5. Plasma flux versus channel pressure drop. Internal 3.5 and 5.5 mm pitch screw-threads and an external 5.5 mm pitch screw-thread were run with the Versapor 0.45 μm membrane.

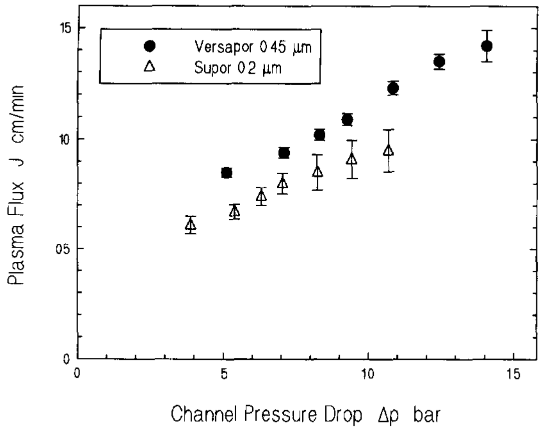

Fig. 6. A comparison of the Versapor 0.45 μm membrane and the Supor 0.2 μm membrane operating with an external 3.5 mm pitch screw-thread.

and Zhang [13] employed a similar external helix system (22 mm pitch) to filter 1.5 to 4.0% solid suspensions using a metal microfiltration membrane. They also found that helical flow increased the channel pressure drop, and attributed the increase to the energy required to set up a rotating flow field.

The results show that the external 5.5 mm pitch screw-thread produces a flux of only $J \approx 0.025$ cm/min. The performance was significantly improved when the 3.5 mm pitch external screw-thread was tested with the Versapor membrane at equivalent flow rates. The lower pitch generated plasma fluxes of 0.1 cm/min and above. The higher velocities and longer path length increased the channel pressure drop to be in the range 0.53 to 1.32 bar. The performance of the 3.5 mm pitch external screw-thread compares favourably with more complex systems, such as vortex mixing [21]. The vortex mixing technique uses a combination of oscillatory flow and thermo-formed membranes to give a plasma flux of ~0.15 cm/min under laminar flow conditions.

The results for the 3.5 mm pitch external design are shown in Fig. 6 for both types of microfiltration membrane. The inlet blood flow increased from $Q = 125$ to 275 ml/min in increments of 25 ml/min. The increase in performance of the 3.5 mm pitch external design over the 5.5 mm pitch can be attributed to the increase in centrifugal acceleration (v^2/r). The helical flow area in the 5.5 mm pitch design is greater than that in the 3.5 mm pitch by a factor of 2.8. At equivalent flow rates through the two systems, the centrifugal acceleration in the 3.5 mm design will be over seven times greater than the 5.5 mm pitch design. As red blood cells are more dense than the plasma phase, the centrifugal acceleration will force them away from the membrane surface, thus inhibiting concentration polarization. The microfiltration results provide very little insight into the complex, three-dimensional fluid dynamics within the blood channel, but we can speculate that the curvature and torsion influence overall vortex strength, which in turn affects the flux. A transition from a 3.5 mm pitch external right-hand-thread to a 5.5 mm pitch design increases the torsion by 150% (see Table 1). This change can promote a helical vortex pattern which opposes the vortex pattern set up from the sudden expansion [14,15], such that the two vortices would counter-act each other. This may explain the poor performance of the external 5.5 mm pitch screw-thread relative to the 3.5 mm design. Further work is required to examine the effect of pitch on microfiltration and ultrafiltration performance.

The external 3.5 mm pitch screw-thread highlights the difference in performance between the two membranes (Fig. 6). The enhanced performance of the 0.45 μm membrane may be due to its greater rigidity such that membrane does not distort at higher flow rates.

Further experiments were performed with the external 3.5 mm pitch screw-thread to assess the flux decline with time. For an inlet flow rate of $Q = 200$ ml/min, the flux declined by 22 and 42% over a 1-h period using the Versapor 0.45 μm membrane and Supor 0.2 μm membrane, respectively. This compares with a flux decline of 32% over a 1-h period reported by Ding et al. [4] for steady flow plasma filtration using 0.5 μm hollow fibre modules.

During each microfiltration experiment the plasma was monitored for signs of free-plasma haemoglobin which would indicate that the walls of the cells had been ruptured at the fluid/membrane boundary. Levels of free-plasma haemoglobin as low as 15 mg/dl can be detected by eye but haemolysis was not observed.

The overall flux enhancement generated by the external 3.5 mm screw-thread design can be highlighted by examining the power dissipated in the flow channel and the power recovered in the filtrate line. Power dissipation in the blood channel is one element we wish to minimise in the system, and it is calculated through the product of channel pressure drop and mean flow rate: ΔpQ. In this analysis we assume that the blood flow rate is much greater than the permeate flow rate, such that the change in feed flow rate between inlet and outlet is insignificant. If we assume that the pressure drop in the filtrate line is small, then the power recovered can be expressed as the product of a mass flow rate and the characteristic velocity squared: $\dot{m}v^2$ (we have ignored the factor of 1/2 for simplicity). If we take the characteristic velocity as the flux J, then the power recovered can be expressed as $\rho J^3 A$. The plasma density is taken as $\rho = 1000$ kg/m^3 and the membrane area is $A = 7900$ mm^2. If we combine the power recovered with the power dissipated then we can express the key filtration parameters in the form of a power ratio:

$$\frac{\rho J^3 A}{\Delta p Q} \tag{4}$$

The non-dimensional power ratio defines the filtration characteristics for a particular system. The power ratio correlates the important quantities measured during microfiltration and consequently can be used as a design tool to predict the performance after scale-up. To clarify this statement, let us consider the simplest form of scale-up, namely an increase in the length of the tubular microfilter. Under these conditions the ratio $A/\Delta p$ will remain approximately constant and the overall power ratio will remain unchanged. This allows the flux to be calculated, provided a value of power dissipation is specified.

To demonstrate the effectiveness of the power ratio we will compared the performance of the internal and external 3.5 mm pitch screw-threads. The filtration results using the Versapor 0.45 μm membrane have been taken from Fig. 5 and Fig. 6 and recalculated to give $\rho J^3 A$ and $\Delta p Q$. The power recovered is plotted against power dissipated in Fig. 7 to highlight the linear nature of the relationship. The results from the other screw-thread designs, although not plotted in Fig. 7, also demonstrated a strong linear relationship between power recovered and power dissipated. We must emphasise that our analysis has been based on results using laminar flow conditions, and that the linear nature of the power ratio may not hold for fully turbulent flow.

The power ratio for the external design is calculated at 1.7×10^{-13} and this compares with a value of 0.5×10^{-13} for the internal screw-thread. This clearly shows that the performance of the external 3.5 mm pitch screw-thread is over three times that for the equivalent internal design.

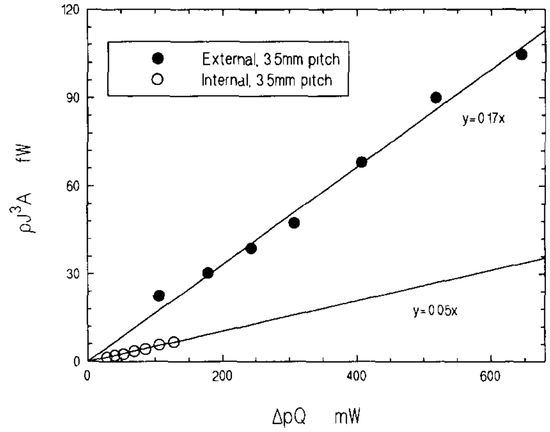

Fig. 7. Power recovered against power dissipated. The performance of an external 3.5 mm pitch screw-thread is compared with an internal 3.5 mm pitch screw-thread using the Versapor 0.45μm membrane.

We can compare the power dissipated in our membrane system with other researchers if we calculate power dissipation per unit membrane area. The external screw-thread design operates in the range 10 to 80 W/m^2. This is the range used by the baffled, pulsatile flow system of Finnigan and Howell [22] but is less than the external helical system used by Holdich and Zhang [13], which dissipates power of the order of 1000 W/m^2.

4. Discussion

The preliminary set of filtration results using screw-thread flow promoters to enhance flux has highlighted some fundamental differences between ultrafiltration and microfiltration. The tubular ultrafilter with 5.5 mm pitch screw-thread inserts worked very well when perfused with quasi-steady flow at moderate flow rates (400 ml/min). The high concentration of BSA (60 g/l) did not provoke long-term flux decline, and the filtration performance reached a level of 75% of the maximum possible for the tubular membranes. The internal screw-thread design compared well in terms of fluid-side resistance with the vortex wave ultrafilter, but the internal screw-thread design is simple to construct and does not require complex flow reversal mechanisms.

The internal screw-thread design, in comparison with a simple bare rod insert, did not enhance the separation of plasma from whole blood. We can conclude that the internal screw-thread geometry is best suited to applications in which the dispersed phase is less dense than the continuous phase.

The problems associated with filtering viscous, heterogeneous bovine blood were overcome by designing an external screw-thread system. The design was required to generate enough centrifugal acceleration to force the red blood cells away from the membrane surface, thus limiting the influence of concentration polarization. The overall microfiltration performance of the screw-thread designs was quantified in terms of a new non-dimensional number, known as the power ratio. The power recovered in the filtrate line was shown to be directly proportional to the power dissipated along the feed channel. The power ratio showed that a transition from an internal 3.5 mm screw-thread to an external 3.5 mm screw-thread tripled the performance. It is hoped that the power ratio will be a useful design tool when we investigate scale-up performance. The internal/external screw-threads are relatively easy to fabricate and require only quasi-steady flow, which means that scale-up to the order of 0.1 m^2 should be straightforward. The screw-thread design also lends itself to scale-down for applications in which the cost of the membrane is the limiting feature, e.g. affinity membranes.

An interesting feature of the results concerns the use of an oscillatory flow component to enhance the flux. There is evidence to suggest that oscillating the flow in a strongly curved pipe (similar in nature to helical flow) does not improve the convective mixing [23], but the majority of researchers have shown that oscillating the flow through a rectangular or tubular membrane channel enhances the membrane performance [3,21,4,22]. Applying oscillatory flow to the internal screw-thread in the ultrafiltration rig had no effect at the high flow rate and improved efficiency by only 39% at the low flow rate. Oscillatory flow was not applied to the microfiltration rigs, but our results suggest that the accelerations and decelerations produced by the peristaltic pump may be important. In an experiment using the external, 3.5mm pitch screw-thread, the tubing at the rollers of the peristaltic pump was increased in area by a factor of 4 and the rotary speed decreased by a factor of 4, thus maintaining a constant mean flow rate. This dampened the flow instabilities and the plasma flux was reduced by approximately 45%.

The measurement of channel pressure in the microfiltration studies has shown that the pressure drop is proportional to the mean flow rate, which indicates laminar flow conditions. Further evidence of the predominantly laminar flow field is the lack of protein denaturation and low haemolysis encountered in the separate studies. The screw-thread flow promoters were designed to combine the flow instabilities generated from flow through a helix and flow over a backward-facing step. The ultrafiltration and microfiltration results show that some form of convective mixing is being generated, but conclusions about the exact nature of the flow field cannot be drawn. A future study will optimise the internal and external screw-thread designs by focusing on flow visualisation, measuring the point of transition from laminar to fully turbulent flow, and indicating the level of shear encountered in the membrane channel.

5. List of symbols

Roman

a	radius of semi-circular screw-thread cross section (m)
A	membrane area (m^2)
b	pitch (as a multiple of 2π) (m)
De	Dean number $= Re^2\kappa$ (–)
H	blood haematocrit (%)
J	filtration flux (permeate flow rate/membrane area $= P/A$) ($m\ s^{-1}$)
J_{clean}	clean water flux ($m\ s^{-1}$)
P	permeate flow rate ($m^3\ s^{-1}$)
Q	inlet flow rate ($m^3\ s^{-1}$)
r	radius of screw-thread curvature (m)
Re	Reynolds number $= va/\nu$ (–)
TMP	trans-membrane pressure (Pa)
v	characteristic velocity ($m\ s^{-1}$)

Greek

κ	curvature (–)
ν	kinematic viscosity ($4.0\times10^{-6}\ m^2\ s^{-1}$ for blood)
ρ	filtrate density (1000 kg/m^3 for plasma)
τ	torsion (–)
Δp	full channel pressure drop (Pa)
Ω	oscillatory frequency (Hz)

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