METHODS TO REDUCE CONCENTRATION POLARIZATION AND FOULING IN MEMBRANE FILTRATION

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Various methods and concepts that are currently being used and proposed to control or minimize concentration polarization and fouling in membrane separation processes are reviewed. A morphological analysis of hydrodynamic ways to prevent the detrimental influence on fluxes is given. The potentials of these different approaches are analyzed and some examples of module designs resulting from the various approaches with special attention to rotary membrane modules are given.

1. INTRODUCTION

Membrane filtration processes are currently mostly used in the production of ultrapure water, the processing of food and dairy products, the recovery of electrodeposition paints, the treatment of oil and latex emulsions and in biotechnology oriented application such as fractionation of fermentation broths and high performance reactors for enzymatic and fermentation processes. However, the present membrane processes for liquid feed streams are complicated by the phenomena of membrane fouling and of concentration polarization in the liquid boundary layer adjacent to the membrane wall.

Concentration polarization and membrane fouling are major concerns in the successful use of membrane-based separation operation, as their net effect is to reduce the permeate flux, thereby resulting in loss of productivity. In many commercial plants, the transmembrane flux may be as low as 2 – 10% of that of pure water flux. Therefore, there is a tremendous potential to reduce or control concentration polarization and fouling in membrane processes and hence alleviate these limitations.

The flux decline due to membrane fouling is frequently masked by changes in membrane properties, or the feed solution, or the development of concentration polarization. The concentration polarization results in a localized increase in the solute concentration on or near the membrane surface. This solute build-up lowers the flux due to an increase in hydrodynamic resistance in the mass boundary layer and due to an increase in local osmotic pressure resulting in a decreased net driving force. However, concentration polarization effects are reversible, since they can be reduced by decreasing the transmembrane pressure or lowering the feed concentration. Fouling effects, on the other hand, are usually characterized by an irreversible decline in the flux.

There are at least three possible approaches to reduce or control concentration polarization and fouling:

1) Changes in surface characteristics of the membrane,

2) pretreatment of the feed and

3) fluid management methods.

In Fig. 1, a morphological analysis of ways reducing concentration polarization and fouling is presented.

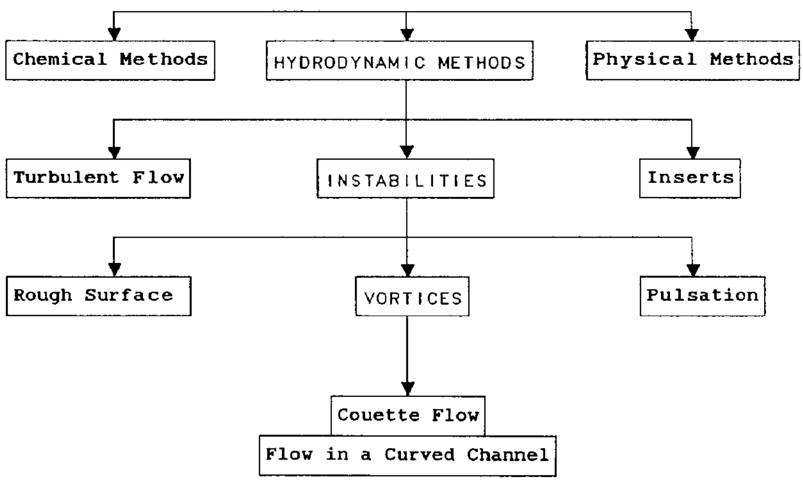

FIG. 1
Typical methods to reduce concentration polarization and membrane fouling

Of the various methods mentioned in Fig. 1, hydrodynamic or fluid management techniques have proved to be quite effective and economical in reducing concentration polarization (CP) and fouling. Thus after describing the classical periodic cleaning procedures together with the physical and chemical methods this paper reviews various hydrodynamic methods and concepts currently being used or proposed to combat CP and fouling.

2. PERIODIC CLEANING PROCEDURES

The common practice to offset fouling effects is to periodically backwash or backflush the membrane and/or shut down the process and clean the membrane by chemical or other means[1,2].

The *backwashing* consists in temporarily shutting off the permeate outlet in order to induce a back filtration from permeate to retentate in the downstream half of the module which balances the ultrafiltration in the upstream half[3]. This retrofiltration can be effective in unclogging the membrane pores, but no permeate is collected during this interval. The flow direction of the circulating fluid must be reversed in order to clean the other half of membrane.

A novel approach to backwashing has been developed by Memtec Ltd. in Australia who produce microfiltration/ultrafiltration systems for particulate and colloid removal. The Memtec system[4] uses hollow fibre membranes with relatively low bubble-point. The feed suspension is pumped across the outside of the fibres and the permeate passes out through the membrane wall (Fig. 2). The flux decline occurs as the colloid is deposited on and within the membrane. This effect is reversed by pulsing the fibre with gas (air, nitrogen, etc.) and backwashing with a gas/permeate mixture. The gas pulse expands the fibres and opens the pores allowing fouling material to be flushed out.

The *backflush* technique uses[5 – 7] the same principle but, in this case bursts of retrofiltration are induced by pressurizing the permeate above the retentate pressure by connecting the permeate circuit with a pressurized tank. This process results in larger retrofiltration velocities than the backwash technique and can be repeated at shorter intervals of the order of one to fifteen minutes. A compromise must be found between the frequency required for keeping the membrane clean and the amount of fluid retrofiltered which decreased the overall efficiency.

The *chemical cleaning* and *disinfection* of the membrane plant are very important operations, especially in food processing. Membranes used in food plants are generally cleaned at least once a day, while those used for the treatment of electrodeposition paints, or for the production of desalinated water, need cleaning less frequently, usually no more than twice a year. A cleaning cycle generally includes the following stages: removal of product from the system, followed by rinsing the system with water; cleaning in one or several steps, followed by rinsing the system with water; disinfection of system.

In the process of solubilization, the deposits are dissolved physically or chemically. The solubility of the deposits is affected by pH and temperature. The chemical resistance of the employed membranes is a distinct advantage in cleaning[8].

All these periodic cleaning procedures complicate the plant lay-out, and bring about a higher consumption of water, energy and chemicals. They also significantly reduce the net operation time. Unfortunately, they seldom are sufficiently efficient and the cleaning operation is facilitated if membrane fouling and concentration polarization effect are reduced as much as possible.

3. PHYSICAL AND CHEMICAL METHODS

Of the above mentioned methods, the most preferred route would be a modification of the membrane chemistry so that attractive or adsorption forces are minimized[9 – 13]. However, this method requires the membrane to be customized for the constituents in each feed stream, which is not very practical. The other possibilities by which membrane properties could be changed are by using a protective pre-coat, or inducing a small electric current[14 – 17] and in biotechnology, by immobilization of enzymes on the

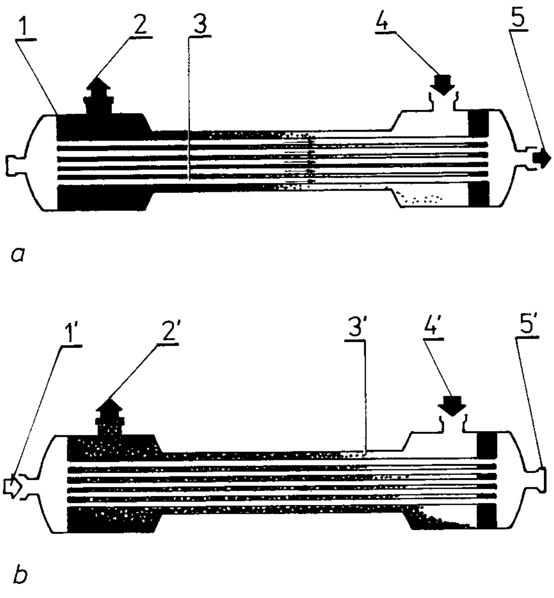

FIG. 2
Operation and backwashing with Memtec cartridge[4]: *a* Operating mode: 1 Polyurethane moulding holds fibres in places, 2 concentrated waste material is rejected from shell, 3 a “bundle” of hollow fibres with microporous walls, 4 feed stream is pumped into shell, 5 clean permeate exits from shell; *b* Backwash mode: 1′ Air pumped in at higher than feed pressure, 2′ concentrated waste build-up is forced out, 3′ air explodes through fibre walls into concentrate stream, 4′ feed stream is pumped into shell, 5′ clean permeate is blocked off

membrane surface[18–20]. The modification of membrane properties may help a reduction in the flux decline phenomena. However, this approach cannot be viewed as a generic solution to concentration polarization and the fouling problem.

The earlier development of membrane processes for commercial and pilot plant applications was based on the strategy of maintaining low transmembrane fluxes. This is only possible in a reasonable module capacity, if an extremely large membrane surface can be accommodated into a compact module. In all of these systems, where handling the feed containing suspended particles or colloids and large macromolecules of high molecular weight, the feed pretreatment in the form of prefiltration is required to reduce plugging or fouling of the module. In these designs, no special effort is made to reduce or control concentration polarization and fouling other than the operation conditions specified by the manufacturers for a given system.

4. HYDRODYNAMIC METHODS

4.1. Turbulent Flow

It appears that the most efficient and natural way to combat deposits and CP is to increase the flow velocity in order to enhance the shear forces acting on the membrane wall. Unfortunately, in the turbulent regime, flow rate is proportional to the pressure drop squared. Higher flow velocities bring about higher pressure drops through the module, which in turn entail a lower pressure available for the filtration and often makes it impossible to connect modules in series. Furthermore, higher flow velocities necessitate bigger and more expensive circulation pumps, higher energy consumption and lower recovery of permeate (ratio permeate flow/feed flow)[3,21].

4.2. Inserts

The mixing near the membrane surface can be achieved by using paddle mixers. This is only feasible in small scale laboratory filtration modules but impractical for industrial application. Several investigators have considered the use of static mixing devices in tubular modules as turbulence promoters. Experiments have shown that compared to empty feed channels, turbulence promoters often give a higher permeate flux for the same feed velocity[22–32]. It is not clear whether this is caused by the decrease in fouling due to removal of deposit from the membrane surface or by the reduction of the concentration boundary layer. Moreover, static mixers (e.g., Kenics mixer) are only suitable for larger tubular designs (Fig. 3), and they always increase the transtube pressure drop and module costs.

The fluidized bed concept needs to operate with tubular membrane modules in a vertical position[33–37]. Fluidizing particles can be either polymer, metal or glass balls. In this case the improved transmembrane flux that is achieved is due to the combination action of scouring and radial mixing. This reduces the thickness of the surface boundary layer and increases the mass transfer coefficient.

These attractive properties of the fluidized bed (a significant modification of CP, and a strong reduction of the boundary layer on the membrane wall) may be used to advantage, for example, in the design of new bioreactors or separators in those cases where chemical or thermodynamic equilibrium between a liquid and a particular solid phase has to be continuously surpassed. It may be possible to elaborate a permeate flux control strategy only based on the solid bed porosity. However, when the feed solution in a membrane filtration process has non-Newtonian properties, and this is common in concentrated biological fluids, they have an enormous influence in determining the operation efficiency[38,39]. This is very important for optimum working conditions of the fluidized bed system.

Segre and Silberberg[40,41] working with dilute suspensions of rigid spheres, were the first to publish their observations of the “tubular pinch effect”, where the particles migrated away both from the tube wall and the tube axis reaching equilibrium at an eccentric radial position. At this position, the spheres became regularly spaced in chains extending parallel to the tube axis. With ultrafiltration, the water flux through the porous wall will still carry particles to the wall, but the “lift” of particles away from the wall (due to the tubular pinch effect) will certainly augment the back diffusive mass transfer.

Bixler and Rappe[42] found that adding glass or plastic beads (ranging in size from 30 to 100 μm) to a protein solution augmented the ultrafiltration flux. They attributed this to (i) the mixing action of the particles and (ii) the mechanical scouring of the membrane surface. However, the use of abrasives is critical for the service life of membranes, pumps, and pipe systems[43].

4.3. Flow Instabilities

Other authors have used more controlled mixing methods such as flow instabilities. These include designing membrane surfaces with organized roughness, pulsation of

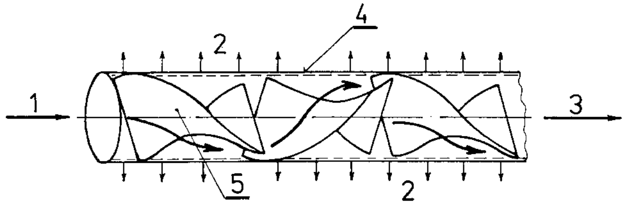

Fig. 3
Principle of radial mixing devices in a tubular membrane module: 1 Feed, 2 permeate, 3 retentate, 4 membrane, 5 Kenics mixing elements

axial and lateral flow, and the use of curvilinear flow under conditions that promote instabilities or vortices.

4.3.1. *Rough Surface*

Peacock et al.[44] and Dorrington et al.[45,46] have developed a vortex mixing device for enhanced gas transfer into blood across a porous membrane. Rather than using a random roughness, these researchers have developed a well-defined rough surface and operational condition to maximize mixing and depolarization. A series of porous furrowed channels are covered with a membrane. A pulsatile reversing flow causes vortices to be formed and ejected during the flow reversal. Unfortunately, these techniques are difficult to scale-up to intermeadiate or large size modules and are often limited by their inordinately high axial pressure drops.

4.3.2. *Pulsation*

The pulsative flow technique[47 – 52] consists in superimposing flow pulsations on the main inlet flow which perturb the CP layer at the membrane and increase the mass transfer rate. At the same time the flow pulsation induces pressure oscillations which can cause small bursts of retrofiltration as with the backflush technique. But unlike this former technique which is discontinuous, the pulsations are applied continuously at a frequency from 0.5 to 2 Hz which probably explains their higher efficiency.

Illias and Govind[50] have solved the complete mass transfer boundary value problem for oscillating flow of a Newtonian fluid in a tubular membrane using a finite difference method. They conclude that the advantage of using pulsed axial flow supercedes the penalty of increased power consumption. Besides energy dissipation, flow reversal also results in reduced net crossflow and hence filtering capacity.

Recently, Bertram and Butcher[52] have used a self-collapsing tube oscillator to induce fluid oscillations down the flow channel of a tubular membrane filter. Improved performance over that without the oscillator was observed. Providing that the collapsible tube has a long life and that the method is not too difficult to scale-up, this approach could be interesting.

4.3.3. *Vortices*

As a result of the dynamic effects of rotation or of streamline curvature, the flow field can become unstable[53]. Classic examples of this include rotational Couette flow, flow in a boundary layer on a concave wall and flow in a curved channel. Of particular interest here is the use of vortices to sweep the CP layer on a porous membrane. Examples of such vortices include those of Taylor, Taylor-Görtler and Dean, resulting from instabilities for the flow between concentric rotating cylinders, along concave walls and in a curved channel, respectively[54]. The controlled surface roughness with flow reversal[44 – 46], and the Taylor vortices[55], in general, result in high wall shear rates, continual renewal and regrowth of the mass boundary layer and generate also external (i.e. centrifugal) forces that sweep the solids off the membrane surface. The net result, of course, is to reduce CP and cake build-up and give improved permeation rates.

Many types[56,57] of rotating membrane filters have been conceived (Fig. 4). In this type of equipment, the wall shear stress is among others a function of the rotating elements such as a rotating cylindrical filtration surface (Fig. 4*a*), a rotating cylinder in

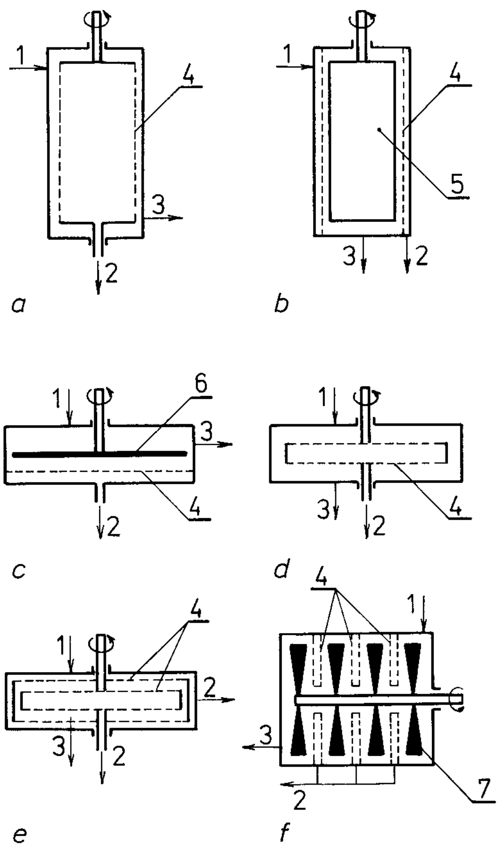

FIG. 4
Types of rotating membrane filters[56,57]: *a* Rotating cylindrical membrane, *b* stationary membrane and solid rotating cylinder, *c* stationary membrane and solid rotating disk, *d* rotating membrane disk, *e* stationary membrane and rotating membrane disk, *f* stationary membrane disks with rotating turbine impeller; 1 feed, 2 permeate, 3 retentate, 4 membrane, 5 solid cylinder, 6 solid disk, 7 impeller

the neighborhood of the stationary membrane (Fig. 4*b*), a rotating disk above the stationary membrane (Fig. 4*c*), a rotating filtration disk (Figs 4*d*, 4*e*) or a rotating turbine impeller positioned in the neighborhood of the stationary filtration disks (Fig. 4*f*). The magnitude of the wall shear rate in a rotating filter can be varied independently of the pressure of the feed suspension in the filter by changing the speed of the rotating elements. High wall shear rates on the membrane surface can result in substantial increases in membrane permeation rates due to reduction of CP and cake build-up above all for suspensions and emulsions with very difficult rheological properties.

Positive results from tests in Sweden with modified plate and frame rotary module, the ABB CROT-filter, have been reported[58]. The CROT-filter consists of a plate and frame module with a rotating plate between each membrane support plate (see Fig. 5). A dynamic membrane can be applied to the surface of the membranes in the CROT-filter. Most of the foulants are then trapped on this precoat layer. The precoat can easily be removed and renewed (e.g., using of a backflush technique) when the flux decreases, which substantially simplifies the cleaning procedure.

A new membrane module design that uses a torsional spring to continually rotate a multiple flat sheet module for a rim displacement of 3.81 cm in an oscillating motion at frequencies of 60 Hz, has successfully filtered difficult solutions and suspensions[59]. Frequent differences in momentum between the membrane and the solution above the membrane result in very high wall shear rates (150 000 s^{-1} is claimed) and effective depolarization. Long term mechanical stability of the system will be crucial to its success.

4.3.3.1. Couette Flow

Most of the rotating membrane filters, which consist of a pair of concentric cylinders with the inner one rotating and the outer one stationary (Fig. 4*a*), have been commercialized by Sulzer in Switzerland and by Membrex and Fenwall in the U.S.A. A membrane is affixed to the inner surface. Above a well-defined angular velocity (which

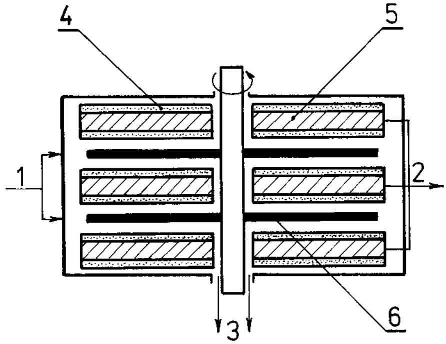

FIG. 5
Schematic illustration of an ABB CROT-filter[58]: 1 Feed, 2 permeate, 3 retentate, 4 membrane, 5 support plate, 6 rotor

depends on curvature, gap size and fluid properties) the azimuthal flow becomes unstable and forms so-called "Taylor vortices" (see ref.[55]). Thus, besides the high wall shear rate, the secondary flow consisting of the regular toroidal vortices rotating inside the annulus is established. The flow through the annulus between two concentric cylinders, with the inner cylinder rotating and the outer cylinder at rest, on which an axial velocity component is superimposed, is of great practical importance. As the angular velocity of the inner cylinder increases, circumferential laminar flow changes to laminar flow with Taylor vortices and then to turbulent flow with Taylor vortices and eventually to turbulent flow. These Taylor vortices or rotating cylindrical tubes of fluid piled one upon the other are shown without and with axial flow in Fig. 6.

Mixing properties and the onset of Taylor vortex flow in the presence of an axial flow and of the influence of a critical geometric ratio have been extensively studied, e.g.[60 – 65].

The flow pattern with axial flow, shown in Fig. 6*b*, is generated by rotating the inner surface of an annulus at some critical angular velocity given by the dimensions of the annulus and kinematic viscosity of the fluid within the annular gap. If a membrane is placed on this rotating surface, the vortices may efficiently reduce the extent of CP by creating excellent mixing normal to the membrane surface. As the angular velocity is increased above its critical value, the degree of mixing intensifies, further improving the efficiency of this filtration scheme. Thus, the membrane can be used more efficiently, leading to a smaller membrane area requirement.

This type of membrane filter has been tested in three major areas of downstream processing in biotechnology – clarification, cell harvesting and protein concentration[66 – 75] and has been used to filter suspensions and emulsions with very difficult rheological properties[76 – 85].

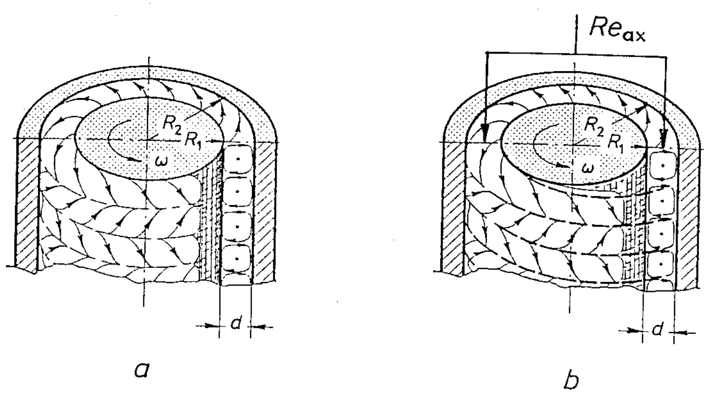

FIG. 6
Taylor vortices for laminar flow in an annulus[53]: *a* Without and *b* with an imposed axial flow component

Kroner et al.[67,68,70] compared the performance of a two concentric cylinder filter (with membranes on the outside of the inner cylinder and the inside of the outer cylinder – see Figs *4a*, *4b*) in turbulent flow for cell harvesting and cell debris removal. Their results indicate that, under similar conditions, permeation fluxes and enzyme retentions were vastly different when comparing the usual cross-flow filter with the rotating membrane filter. Mateus and Cabral[72] used a rotary membrane system in the downstream processing of fermentation media. Their results show clearly the best performance of the rotary membrane system, when compared with hollow fibers and plate and frame modules (Fig. 7). Belfort et al.[74,75] measured the permeation rates of deionized water, fetal bovine serum medium, and a commercial serum-free medium through microfiltration and ultrafiltration membranes. Their results indicate that the centrifugal force acts both on the fouling material and on the fluid, causing an increase and a decrease in the wall flux, respectively. The experimental results suggest that the former effect dominates in this case.

Mikulasek et al.[82,84] and Belfort et al.[85] studied the microfiltration of a dilute suspensions of well-defined spherical particles using a rotating annular filter with a view to understanding the mechanism of fouling. A rotating filtration system with the membrane placed on the inner rotating cylinder (BENCHMARK™, Membrex, Inc., Fairfield, NJ, U.S.A., see Fig. 8), which is commercially available, was used. It is a compact benchtop system designed for small-scale purification. Table I summarizes some technical data of the apparatus and typical operation conditions derived from the experiments.

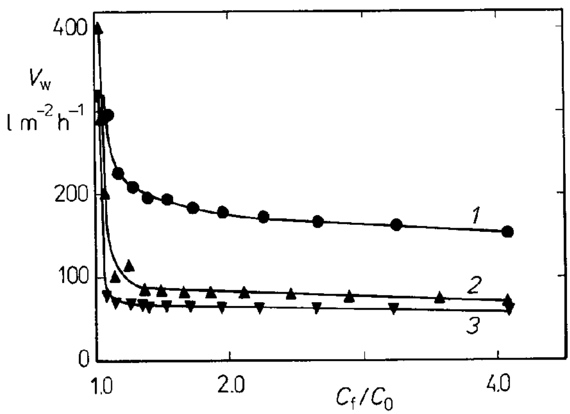

FIG. 7
Effect of fluid hydrodynamics on the performance of different cells at transmembrane pressure 83 kPa, according to Mateus and Cabral[72]: *1* Rotary membrane system Re_{ax} = 40 (d_h = 2 d), Ta = 2 345; *2* hollow fibers Re_{ax} = 636 (d_h = D); *3* plate and frame Re_{ax} = 7 850 (d_h = 2 H). (The experiments with cell culture feed were performed using 100 000 MWCO polysulfone membranes.)

The effect of the angular velocity on the cake resistance of the rotary membrane system for three suspensions of particles is shown in Fig. 9. In all cases a substantial decrease of cake resistance with increasing speed of rotation is observed, and at the highest rotor speed (ω = 420 rad s^{-1}), cake formation for the suspension containing particles of the mean diameter of 2.02 μm was negligible.

From the results shown in Fig. 9, a decrease in the mean particle diameter from 25.7 to 11.9 μm resulted in an expected increase in fouling (i.e. R_c increased) for a given value of the angular velocity. Unexpected behaviour, however, is observed for the suspension containing particles of the mean diameter of 2.02 μm. A detailed explanation for this behaviour is difficult without further measurements. However, it should be

TABLE I
Technical data and typical operating conditions of the rotating filter BENCHMARK™ (see Fig. 8)

Radius of rotating inner cylinder	22.05 mm
Annular gap width	2.43 mm
Membrane cartridge length	170 mm
Effective membrane surface area	200 cm^2
Operational pressure range	0 – 0.27 MPa
Angular velocity range	0 – 420 rad s^{-1}
Taylor number range, *Ta*	0 – 7 430
Axial Reynolds number range, Re_{ax}	30 – 125

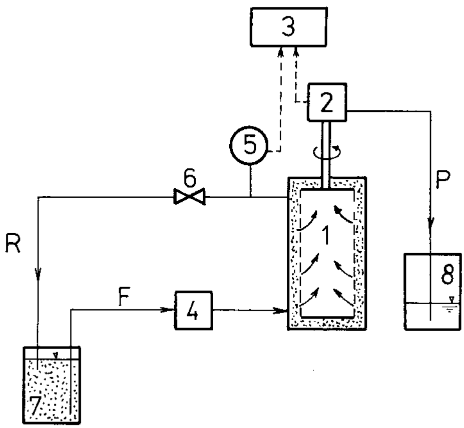

FIG. 8
Schematic diagram of rotary membrane filter BENCHMARK™: *F* Feed, *P* permeate, *R* retentate; 1 rotating membrane filter, 2 magnetic drive assembly, 3 electronic control unit, 4 peristaltic pump, 5 pressure transducer, 6 retentate pinch clamp, 7 feed solution vessel, 8 permeate collection vessel

noted that the large particles (mean diameter 25.7 and 11.9 μm) are made of the same polymeric system (styrene/divinylbenzene) and with the same suspension polymerization process. The smaller particles (mean diameter 2.02 μm) were made from a different polymer system (styrene/polyvinyltoluene) with a different process (emulsion polymerization). For the latter case, the process is thermally initiated and involves the use of an ionic surfactant (sodium dihexylsulfosuccinate). Consequently, the 2.02 μm beads are negatively charged with a persulfate endgroup, while the larger particles with far smaller surface area were made by means of a non-ionic stabilizer, polyvinyl alcohol, and are very slightly negatively charged. Thus, the amount and density of surface charge is expected to be very different for the 25.7 and 11.9 μm and for the 2.02 μm size particles.

On the basis of Fig. 9 we could speculate that the smaller particles are repelled in another way if the negative charged membrane (sulfonated polysulfone) at the given pH of solution is used. Moreover, the centrifugal force that tends to drive away from the membrane the particles and/or wall shear rate due to turbulent Taylor vortices ($\omega > 210$ rad s^{-1} and $Ta > 3\,500$) should be more effective for the particles removal in the case of the loosely associated small charged particles than with the larger particles.

Results obtained with the rotational annular filter confirm the assumption that the use of Taylor vortices, which result from sufficient azimuthal flow in a cylindrical annulus, will help to depolarize the solute build-up on membrane lining the annulus. In addition to the effects of the Taylor vortices mainly the applied high wall shear rate and the uncoupling of shear generation from axial flow and the operational pressure contribute largely to the much higher performance of the rotating filter comparing it with tangen-

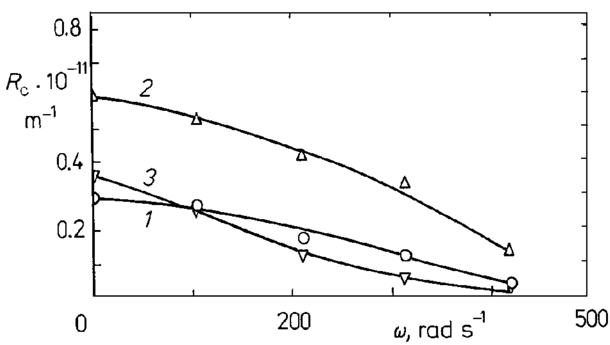

FIG. 9
Cake resistance versus angular velocity for suspension of 25.7 (*1*), 11.9 (*2*) and 2.02 (*3*) μm latex particles; hydrophilized polysulfone microfiltration membrane (mean pore diameter 0.45 μm, R_m = 1.1 . 10^{-11} m^{-1}, filtration area 200 cm^2) was used. (Concentration of latex particles in suspensions was 0.1% (w/w).)

tial flow devices[83]. Assuming that very high tangential velocities have to be applied for a "clean" membrane surface[56], the development of the rotating annular filter becomes of increasing interest.

4.3.3.2. Flow in a Curved Channel

When azimuthal laminar flow of a fluid along a curved surface is increased, centrifugal force pushes fluid elements radially outwards. To maintain continuity of mass, an equal amount of fluid elements needs to move inwards in the reverse radial direction. At a well-defined flow rate this backflow (or secondary motion) is augmented by the formation of vortex instabilities of spiral flows[53,54].

The new bioengineering spiral stack membrane module[86 – 88], which has been commercialized by Bioengineering AG, Switzerland, is characterized by spiral solid-walled half-tube which is placed onto a flat sheet synthetic membrane (Fig. 10). Fluid is introduced into the center of the circular module and flows in the half-tube spirally outward. At high enough flow rates, secondary vortex flow is induced that centrifugally sweeps the membrane surface depolarizing the solute build-up. The advantages of this arrangement are summarized as follows:
– Filtration performance is enhanced due to spiral eddies on the membrane surface,

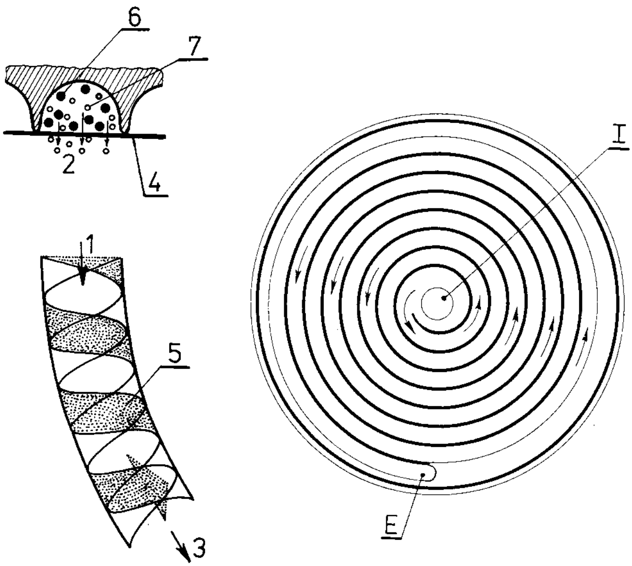

FIG. 10
Schematic diagram of the vortex flow in a spiral half-tube onto a flat membrane[88]: *I* Inlet, *E* exit; 1 feed, 2 permeate, 3 retentate, 4 membrane, 5 secondary flow eddies, 6 suspended particles, 7 product

– power demand is minimal since relatively low volume flow rates produce high shear rate on the membrane surface,
– prefiltration is not required due to large cross section of feed channels.

Recently, Chung et al.[89 – 91] have designed, built and tested a curved channel duct based on continuously maintaining the streamwise flow for incipient production of vortices as a result of flow along a 180° curved surface. Vortices are produced that twist and spiral in the streamwise direction. This provides the optimal fluid mechanics conditions for best long-term performance. By placing a test membrane section in the flat region, increased permeation flux (up to 30%) in the presence of weak Dean vortices, compared with pure cross-flow without such vortexes. Detailed results confirming the existence of Dean vortices in the curved channel duct module and filtration results with and without vortices are presented[90,91].

5. CONCLUSIONS

From this review, it is clear that various innovative methods have been proposed to combat concentration polarization and fouling. These have been partially successful, and in many cases were found to be difficult to retrofix existing installations. In some cases modifications were difficult from engineering and economic design considerations.

Operating in the turbulent flow regime has the advantage of thinner mass boundary layers but the disadvantage of increase pressure drop and pumping costs. Inserts are only suitable for larger tubular designs and one of the critical points in a fluidized bed system is accurate control of the fluidization, which necessitates complicated control equipment. Applying the pulsations to the feed stream is the most efficient method to control particle fouling. However, it needs to be optimized (the shape of the velocity profile is a function of the channel geometry as well as the pulsation frequency), and it does not solve the important problem of the membrane clogging with colloids or macromolecular material. The use of vortices to sweep the concentration polarization layer and particle deposit on a porous membrane is very efficient, since very high shear rates can be obtained at low flow rate. Classic examples of these unsteady flows include Couette flow, flow in a boundary layer on a concave wall and flow in a curved channel.

Different types of modules have been developed which are based on the principle that the membrane itself is rotating. One such module utilizes rotary annular flow (see Fig. 8). Basically the Couette flow system, with internal cylinder rotating is employed in order to:

a) achieve high azimuthal shear rate along the membrane which is mounted on the internal cylinder;
b) increase radial mixing of the liquid by working in the Taylor vortex domain;
c) utilize natural convection in a centrifugal field.

These effects can improve the mass transfer considerably. A disadvantage of devices using Taylor vortex flow are the high energy consumption to rotate the equipment, possible sealing and membrane replacement difficulties and most importantly difficulties in scaling-up the capacity of the module. However, the advantages of this type of device are excellent bulk fluid mixing, high wall shear rates, and weakly decoupled axial cross-flow with transmembrane pressure. In this context it is of interest to note that the rotating annular filter (Fig. 8) has good capability for the integration with other separation steps with respect to automation or continuous processing, due to stable operational conditions and the possibility to operate with single passing.

In order to overcome some limitations associated with rotating annular filter devices, several recent publications report also on the physical phenomena and potential of Dean vortices to destabilize polarization layers in pressure driven membrane modules based on curvilinear flow. However, this latter topic needs further research.

SYMBOLS

C_0	initial concentration of cells in the feed, kg m^{-3}
C_f	final concentration of cells in the retentate, kg m^{-3}
d	annular gap width, m
d_h	hydraulic diameter, m
D	diameter of hollow fiber, m
H	channel height, m
R_c	resistance of cake layer, m^{-1}
R_m	resistance of membrane, m^{-1}
R_1	outer radius of inner cylinder, m
R_2	inner radius of outer cylinder, m
Re_{ax}	axial Reynolds number, $Re_{ax} = d_h u/\nu$
Ta	Taylor number, $Ta = [\omega R_1 d/\nu]\ [2d/(R_1+R_2)]^{0.5}$
u	axial feed velocity, m s^{-1}
V_w	permeation flux, l m^{-2} h^{-1}
μ	dynamic viscosity, Pa s
ν	kinematic viscosity, m^2 s^{-1}
ω	angular velocity, rad s^{-1}

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