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Methods Employed for Control of Fouling in MF and UF Membranes: A Comprehensive Review

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Abstract: Membrane-based processes are very susceptible to flux decline due to concentration polarization and fouling problems and the concept of fouling control via process optimization, membrane surface modification, and cleaning have been the focus of research in wastewater and water treatment. MF and UF membranes are utilized in many areas of industry. The main sector of application includes water and wastewater. There has been emphasis on the various methods used to reduce and, where possible, eliminate fouling. This review is a comprehensive insight into the wide range of techniques used in the control of fouling in both MF and UF membranes. It also addresses the amount of research that has gone into the various techniques used and the results achieved after experimental work.

Keywords: Membrane fouling, pretreatment, surface modification, cleaning, microfiltration, ultrafiltration

INTRODUCTION

The water and wastewater industry has been faced with many challenges over the last two decades and is currently concerned with achieving efficient and economic methods of treatment. The most common form of treatment of

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portable and drinking water as well as surface water sources involve chemical and physical removal of particulate matter. Membrane systems are becoming the main focus of water treatment and the choice of membrane, module configuration, process and operating parameters, and pretreatment amongst others are very important in the efficiency of separation. They are very promising because of their potential to remove particles, including microorganisms, organic pollutants, inorganic salts, and to achieve biologically stable water to limit microbial regrowth in the distribution system (1).

Decrease in the permeate rate during membrane process exploitation attributed to membrane fouling is recognized as the main problem in the application of membrane technologies (2). Several types of fouling can occur in membrane systems including inorganic fouling, particulate and colloidal fouling, organic fouling, and biofouling (1). Pore blocking and cake formation are considered as the two main mechanisms of membrane fouling while other factors such as adsorption, particle deposition within the pores, and changes to the cake layer affect membrane fouling through the modification of either or both mechanisms (2–6). Pore blockage increases the membrane resistance, while cake formation creates an additional layer of resistance to permeate flow (3, 4). Severity of these phenomena depends on the nature of the particle, the operating conditions such as pH, ionic strength, pressure, and concentration, the nature of the membrane (5). Development of effective methods to control fouling is based on understanding of the fouling mechanism and the influence of the process parameters on the membrane fouling. To discuss approaches to mitigate membrane fouling we will first outline the main particularities of this process.

Generally, for microfiltration and ultrafiltration, two types of fouling phenomena are distinguished. The first is macrosolute or particle adsorption, which refers to the specific intermolecular interactions between the particles and the membrane that occur even in the absence of filtration. It is usually irreversible, adhesive fouling. In water treatment applications, the foulants are usually adhesive due to hydrophobic interactions, hydrogen bonding, van der Waals attractions, and extracellular macromolecular interactions amongst others (7). The second type is known as filtration-induced macrosolute or particle deposition, which is often reversible, nonadhesive fouling, where the accumulation of cells, cell debris, and other rejected particles on the top surface of the membrane is prominent. It occurs as external fouling or cake formation (8). Reversible fouling resulting from cake formation was found to be only weakly dependent on membrane surface chemistry; in contrast, irreversible fouling exhibited a marked dependence on surface chemistry (9).

Membrane fouling is an extremely complex physicochemical phenomenon. Usually several mechanisms are involved simultaneously. Thus in case of protein-containing solutions it was suggested that it began with protein aggregates depositing on the membrane surface, thereby blocking its pores (10). Disulphide linkages, van der Waals forces, electrostatic interactions, hydrophobic interactions, and hydrogen bonding all contributed to membrane fouling by proteinous substance, mostly through adhesive fouling (11). On the contrary, for filtration of river water, cake formation on the surface of the membrane resulted in more pronounced ultrafiltration membrane fouling than the adsorption of small substances inside the pores of the membrane (12, 13). UF membrane fouling was dominated by the cake layer formation attributed to the accumulation of dissolved organic materials and suspended colloids in the raw water. The particles are driven to the membrane surface by the flow of permeate to form a cake layer on the membrane unless the shear rate is very high to prevent cake formation. The undetachable cake layer accumulates on the membrane and results in fouling in the long term (12, 14, 15).

Biofouling is another major problem, which destroys the structural integrity of the membrane, and this leads to subsequent irreversible membrane damage, shortened membrane life, increased operational and maintenance costs, and reduced efficiency (16). It is initiated by irreversible adhesion of one or more bacteria to the membrane surface followed by growth and multiplication of the sessile cells at the expense of feed water nutrients. It can eventually form a confluent lawn of bacteria, otherwise known as a biofilm on the membrane surface (17). Chemical properties of membrane surface, its roughness, pore shape, and size distribution are found to be the main factors controlling the biofouling potentials (18).

The complexity of membrane fouling predetermines the exploiting of a variety of approaches to control this adverse process. Here these approaches are categorized under four main topics: (i) Pretreatment of feed; (ii) Membrane materials/surface modification; (iii) Operating parameters; and (iv) Cleaning procedures. Approaches discussed in the first three topics are focused on preventing or mitigation of the membrane fouling, whereas methods of the forth topic are assigned to cope with consequences of the membrane fouling.

FEED PRETREATMENT IN MEMBRANE FOULING CONTROL

This approach is commonly used to remove and filter the particulates that may be causing module clogging or preventing particulates or macromolecules from depositing on the membrane surface. It is very important as it contributes to reducing fouling effects and it involves physical and chemical processes. The physical processes usually include prefiltration to remove any suspended particles that may plug the module or adhere to the membrane surface. Heat treatment followed by settling is another physical process utilized in the diary industry to remove immunoglobulins and fats from cheese whey prior to UF (19).

Chemical processes on the other hand involve precipitation, coagulation, or flocculation and the use of proprietary chemicals as antiscalants or disinfectants. pH-adjustment of the feed causes foulants to be far off from their isoelectric points, which ultimately reduces their tendency to form a gel layer (20). Thus, removing particulate matter and thereby preventing particles from the deposition on the membrane surface involves both physical and chemical processes. The former includes prefiltration to remove suspended particles that have the tendency to adhere to the membrane surface; settling after heat treatment to remove fats, etc. from cheese whey prefiltration. Precipitation and coagulation are also other forms of chemical processes. The addition of flocculation-coagulation agents limits membrane fouling by aggregation of the colloidal fraction, thus reducing the internal clogging of the membranes (21). Coagulants aim to reduce and eliminate internal clogging of the membrane by depositing the colloidal particles and helping them form sufficiently large aggregates to facilitate obtaining higher rates of permeate flux. Chemical coagulants can destabilize colloidal particles by four distinct mechanisms, which include (i) double layer compression, (ii) charge neutralization, (iii) enmeshment in a precipitate, and (iv) interparticle bridging.

Hydrophilic colloids owe their stability to solvatation in addition to surface charges, and the destabilization of particles is essential in order to bring them in contact and aggregate (22). Research was carried out on the addition of coagulants to enhance the formation of larger particles from the initial molecules that would be readily swept of the membrane surface. The effect of using alum, polyaluminium silicate sulfate (PASS), and lime as coagulants on the performance of cross-flow microfiltration of domestic wastewater was investigated as shown in Fig. 1. The overall results showed

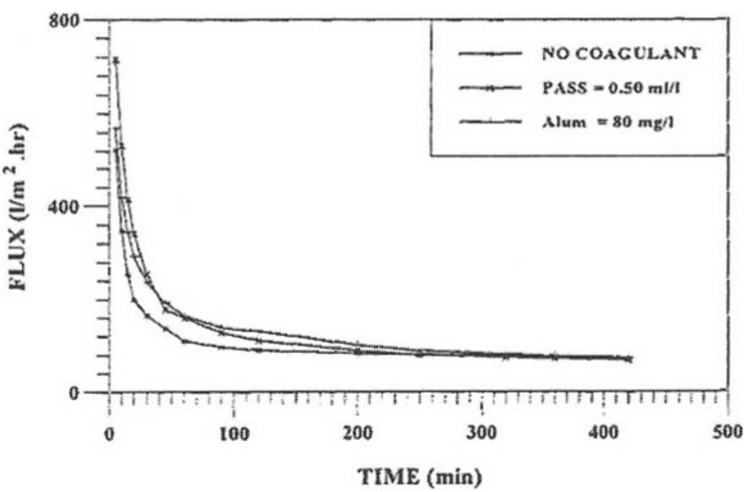

Figure 1. Permeate flux obtained with the use of PASS and alum (22).

that the permeate quality was not significantly affected by the addition of alum or PASS, which was attributed to the pore size of the dynamic membrane. The deposition of particles was also found to proceed in relation to the standard law of filtration. Lime was found to be unsuitable as a coagulant with respect to the pH used in the study (22). There was also a study of the treatment of oily wastewater produced from posttreatment of refinery processes using flocculation and microfiltration. The results showed that the rate of fouling on membranes decreased and the quality of the permeate flux increased with flocculation as pretreatment (23). A detailed study was carried out to identify the membrane fouling potential that different fractions of NOM contributed and correlate the physiochemical properties of NOM and membranes and the adsorption of humic substances on membranes. The mechanism of coagulation relating to UF and optimum conditions of the combined processes was also investigated. Conclusions to the study suggested that hydrophobic organics adsorbed more rapidly than hydrophilic organics on the membranes. It was also found that the combined coagulation with membrane processes showed lower flux decline rates than in UF alone. There was also evidence of reduced levels of fouling on the membranes (24).

The use of flocculants in improving separation efficiency during cross-flow microfiltration was investigated, and it was shown that the addition of flocculants gave a significant improvement of the performance of hollow fiber microfilter (25). The research of in-line cross-flow microfiltration led to conclusion that permeates flux was enhanced and that the rate of enhancement was dependent on the coagulation dose, flocculation time, and cross-flow velocity (26).

Cake formation control required the prevention of particles reaching the membrane and also the flushing out of the particles. Diatomaceous earth was utilized as a filtration aid, and it was discovered that mixing a filtration aid to the feed stream led to a more permeable filtration cake. The other techniques that have been used to prevent the particles reaching the membrane include the use of abrasives, filtration aids, coagulants, and electrofiltration. The other end of the spectrum involves the removal of particles already located in the membrane or at the surface. Some of the techniques that have been employed include periodic backwashing, ultrasonic fields, and periodic flow (27). The effect of ozonation on permeate flux was studied extensively by using a polysulfone ultrafiltration membrane. The filtration was carried out by permeating chemical wastewater, which was treated by a combination of ozone and membrane filtration methods. This study focused on ozone-use to reduce membrane fouling in the process and to prolong the life expectancy of the membrane. It was concluded that the flux rate increased by about 12% as the ozone input increased. It was also realized that ozonation did not have a significant role to prevent membrane fouling, and it made the permeate flux increase, but ozone and hydrogen peroxide was more effective (28).

MEMBRANE MATERIAL/SURFACE MODIFICATION IN DECREASE OF MEMBRANE FOULING POTENTIAL

This is another control option, which mainly involves changes to the membrane surface and modifications to the membrane surface. This method is mainly used to combat and eliminate adhesive fouling. The membrane material influences fouling to a greater degree in ultra- and nanofiltration, largely due to the tendency of some materials to adsorb solutes more readily than others (6). The effects of solute adsorption in MF may not be very severe, but the solutes contribute significantly to flux reduction by reducing the pore sizes on the membrane. There are different methods that have been employed involving surface membrane modification with the potential to reduce fouling. On the other hand, the attractive alternative is the production of new low fouling membranes by modifying commercial membrane surfaces to render bacteriostatic properties and thereby to effectively inhibit microbial growth (18). The appropriate choice of membrane material can also lead to looser binding of the solutes to the membrane surfaces, which subsequently reduces any membrane-solute interaction and leads to a reduction of membrane permeability (6).

Most commercial membranes are made from hydrophobic polymers like polysulfone, polyethersulfone, polypropylene, polyethylene, and polyvinylidenefluoride (PVDF) due to their excellent chemical resistance and thermal and mechanical properties (29, 30). Hydrophobic membranes, however, are easily susceptible to fouling, i.e., nonspecific adsorption of solutes on the membrane surface and pores resulting in severe decline (31–33). It has also been generally acknowledged that membranes with hydrophilic surfaces are less susceptible for fouling and often reversible (34–40). Thus, the ideal membrane combines superior bulk properties of hydrophobic polymers with surface chemistry of hydrophilic materials (29). Membrane fouling has to be kept to a minimum in order to maintain the economic viability of a membrane process, and over the last few years researchers have devised various strategies to reduce fouling of membrane surfaces. These methods include chemical, low-temperature plasma, and photochemical techniques (41–45).

The conventional methods for color removal from wastewater include chemical coagulation, flotation, chemical oxidation, and adsorption (46–49). Over the last few years, membrane-based processes have the potential and may be an attractive alternative for the treatment of dye containing effluent. The use of dynamically formed zirconium oxide-polyacrylate membrane in a tubular shape to treat textile dye house effluent was also reported and a 95% dye recovery was observed (50, 51). Spiral wound modules also got similar results (52).

Surface modification of membranes is an attractive approach to change the surface properties of the membrane while preserving its macroporous structure in a defined selective way. Considerable efforts to impart antifouling properties on hydrophobic surfaces have resulted in two techniques, namely (i) coating and (ii) grafting (53).

Coating involves the use of a solution containing the polymer(s) bearing the antifouling property. The membrane to be used is then dipped into the solution, hence coating it in the solution (54, 55). Grafting, on the other hand, achieves the covalent immobilization of hydrophilic species onto the membranes from solutions (56–59). A combined backpulsing and membrane surface modification was developed to reduce both adhesive and nonadhesive fouling for cross-flow filtration of bacterial suspensions, clay suspensions, and oil emulsions. A sixfold enhancement was obtained by a combination of backpulsing and hydrophilic surface modification when compared to a fivefold permeate enhancement obtained by backpulsing alone. There was also a 1.3- and 2.7-fold permeate enhancement by backpulsing alone and with a combination of backpulsing and surface modification for crude oil filtration (60).

Photo-induced grafting is a particularly useful technique for the modification and functionalization of polymeric materials due to several features. These include low cost of operation, mild reaction conditions, selectivity to absorb UV light without affecting the bulk polymer, and permanent alteration of the membrane surface with facile control of the chemistry (7). In an attempt to develop membranes with lower fouling properties, photo-induced grafting copolymerization was used for the modification of membrane surfaces (18). Two types of hydrophilic monomers, 2-acrylamido-2-methyl-1-propanesulfonic acid (AMPS) and quaternary salt of 2-dimethyl aminoethylmethacrylate (qDMAEMA), were photografted to the surface of commercial polyethersulfone (PES) microfiltration membranes. These two monomers were chosen for this application for their high hydrophilicity and water solubility. The membrane affinity to biofouling was tested experimentally in the presence of *E. coli* bacteria, and it was found that the number of bacterial cells able to reproduce was much lower for qDMAEMA-grafted samples compared with unmodified PES membranes (Fig. 2). Of the two membranes studied, the modified membrane had a significantly smaller force of adhesion, which backed up the fact that it would aid the development of new membrane materials with low or zero fouling properties.

Another study (61) focused on the preparation of ultrafiltration membranes with the emphasis on poly(acrylonitrile-co-acrylamide). The ultrafiltration membranes in this study were prepared from acrylonitrile homopolymer, which is hydrophobic in nature and from a mixture with copolymers with increasing acrylamide content. The three membranes compared in the experiment were made from polyacrylonitrile (PAN), copolymers with 20% acrylamide content (PAN-1), and copolymers with 30% acrylamide content (PAN-2). The acrylamide insertion increases the hydrophilicity of the membrane, decreases the dispersion force component of surface energy, and reduces the overall electrostatic charge on the membrane. In conclusion, the results derived from the experiments showed that in comparison with

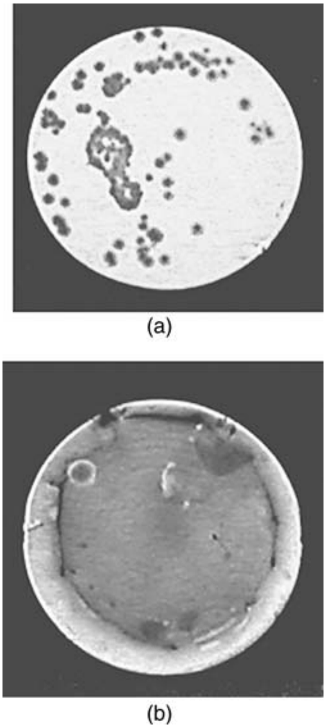

Figure 2. Photographs of (a) initial PES membrane and (b) PES membrane with grafted qDMAEMA (18).

polyacrylonitrile, the acrylamide containing copolymers yielded membranes with a higher hydrophilicity and reduced negative electrostatic charge. With respect to permeate flux and recovery, there was an increase for all the membrane types and at any given pH value, less fouling of the membrane surface occurred with acrylamide containing membranes.

However, the coating and grafting techniques involve the following disadvantages, which include easy erosion of the coated layer, resulting in unsatisfactory reliability and durability of the modified surfaces. The surface grafting technique also poses process complications and time-consumption, extensive use of organic solvents, and monomers resulting in increased costs (58). The surface modification procedures and the associated grafting mechanism for the modification of PP membranes were described in which the first involved the attraction of benzophenone and hydrogen to generate surface radicals and semipinacol radicals, which combine to form surface photoinitiators in the absence of monomer solutions. A good solvent then washes off the unreacted benzophenone. The monomer solutions are then contacted with the active substrate, and the surface initiators initiate the graft polymerisation when exposed to UV irradiation. The grafts attach to both the exterior surface of the membrane and the interior pore surfaces, although the grafting density of the latter decreases with distance from the membrane surface due to light attenuation (62).

The combination of backpulsing and surface modification resulted in an effective method for fouling reduction at low foulant concentrations, and the desired surface characteristics including hydrophilicity and varied ionic charges were realized using the photo-induced graft polymerization method. The permeate volumes with backpulsing for the hydrophilic, charged membranes were greater than that for the hydrophobic, neutral membrane. However, one of the findings was that with time, the flux with and without backpulsing was less dependent on the membrane surface chemistry. This is probably due to the bacterial deposit on its surface. On the other hand, the long-term net flux with backpulsing was approximately twice that without backpulsing. The other important find in the research study was that the effectiveness of the surface modification in fouling reduction with backpulsing decreased with increasing *E. coli* concentration (7). The effective use of grafting techniques in the reduction of irreversible protein fouling by membrane surface modification was also confirmed (58). Leow et al. described the use of nylon screens incorporated into hollow fiber microfiltration systems for wastewater treatment and the use of newer module designs (3, 63–65). The membrane material used had a major influence in ultrafiltration and nanofiltration due to the ability of materials to adsorb solutes better than others. The relationship between the concentration of particles in solution and the adsorption onto membrane surfaces was illustrated and showed that the permeate flux decreased in relation to the concentration of BSA in solution and the amount adsorbed on the surface. The authors used three types of membranes and the results of the experiments showed that with a cellulose acetate membrane, only one adsorption layer was found, whereas on increment of BSA in the solution, more layers were adsorbed onto polysulfone and polyamide membranes. The principle shows that the suitable choice of membrane leads to a lesser binding of solutes, further reducing the membrane-solute interactions that lead to permeability reduction (66).

In a study of the UF of whey using polysulfone membranes (67) membrane resistance, R_m, fouling resistance, R_f, and polarized layer resistance, R_p, were analyzed. While operating at a low pressure, it was observed that the R_p was small and that the culmination of R_m and R_f was, in fact, more pronounced and had a more direct influence on the flux decline. The reverse trend was observed in the case at a higher pressure. The fouling resistance, R_f, however, was independent of operating conditions while pressure, flow rate, and whey concentration changes affected R_p.

In contrast to surface modification techniques like alcohol wetting and surfactant adsorption, graft polymerization can modify membrane surface properties permanently, and its applications included filling membrane pores to improve selectivity of pervaporation membranes (68, 69). There has also been previous research which has correlated low surface wettability with non-specific sorption of both detergents and proteins. Therefore, graft polymerization to increase the wettability of membrane surfaces offers promise to reduce their ability to interact with species present in solution and thus reduce their potential to foul during filtration (70). There has also been more recent work where graft polymerization technology has been applied to reduce fouling by natural organic matters (NOM) during portable water production, including RO and NF (71–82). A UV-assisted photochemical graft polymerization technique was used to produce modified PES ultrafiltration membranes that could exhibit reduced interaction with natural organic matter, as a route to reduce the fouling caused by NOM.

There were six different hydrophilic membranes that were evaluated for their ability to reduce fouling by NOM (9). The monomers included neutral monomers, N-vinylpyrrolidone (NVP) and 2-hydroxyethyl methacrylate (HEMA); weakly acidic monomers, acrylic acid (AA) and 2-acrylamidoglycolic acid (AAG); and strongly acidic monomers, 3-sulfopropyl methacrylate (SPMA) and AMPS. The grafting increased membrane surface wettability and shifted the membrane pore distribution to smaller sizes, which increased the NOM rejection. The weakly acidic monomer, AA, produced the lowest fouling membrane when it was used to treat an NOM feed obtained from potable surface water.

A study (53) was also done when PVDF microporous membranes with surface-immobilized poly(ethylene glycol) (PEG) were prepared by the argon plasma-induced grafting of PEG. A schematic diagram showing the mechanism of grafting is shown in Fig. 3. The PEG was precoated on the membrane surface by dipping the membrane in a solution of $PEG/CHCl_3$ prior to the argon plasma exposure. PEG is well known for its extraordinary ability to resist protein adsorption. This particular property is as a result of its hydrophilicity, large excluded volume, and unique coordination with the surrounding water molecules in an aqueous medium. Surface-grafted PEG has rendered UF membranes resistant to oil and protein fouling as reported in the past. The results of the work showed that water flux decreased with an increase in surface PEG graft concentration, while the mean pore size remained almost unchanged. Protein adsorption and water flux experiments revealed that the PEG-g-PVDF membrane exhibited very good antifouling property.

Other techniques that have been employed to impart surface hydrophilicity to conventional hydrophobic membranes to improve their fouling resistance properties include radiation and photochemical grafting of hydrophilic polymers (56, 71, 83, 84); glow discharge low-temperature plasma treatments (59, 85–88); covalent attachment of hydrophilic polymers and functional monomers (89–91) and the coating of a thin layer of hydrophilic polymer on membrane surface by physical adsorption (92–95). Cleaning helps to improve the effects of membrane materials after layers have developed, and it may also make the solute easier to displace. The technique involving

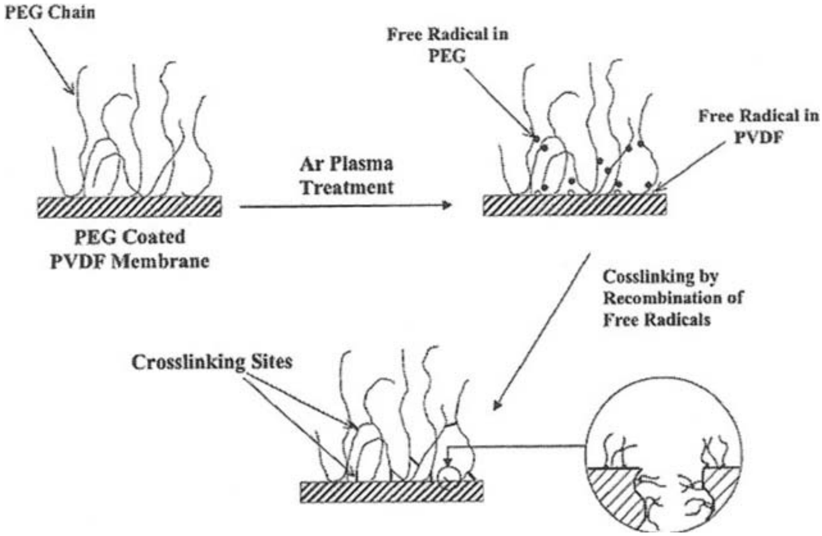

Figure 3. Schematic representation of the plausible mechanism of plasma grafting of PEG onto the PVDF microporous membrane (53).

physically coating water-soluble polymers or charged surfactants onto the membrane surface for temporary surface modification, using nonionic surfactants and hydrophobic ultrafiltration membranes, was investigated (94). The use of LB techniques for the formation of ultrathin films on the membrane was also investigated via the use of surface pretreatment using various polymers, and the results obtained showed a steady increase in the initial UF flux and a slower flux decline (96). Methylcellulose was found to be the most effective polymer used in the enhancement of UF flux. First usage gave a flux advantage of up to 40%, while subsequent cycles showed up to 100% improvements.

The idea of coating hydrophilic polymers on the membrane using heat curing was further investigated (97). The grafting of monomers unto the surface of the membranes by electron beam irradiation was extensively studied for membrane surface modification with hydrophilic polymers (98, 99). Significant changes were observed in the performance of the asymmetric polyethersulfone ultrafiltration membranes, with permeate flux improving at certain combinations of experimental parameters. A new technique was developed and evaluated for making new types of surface modified UF membranes, and the advantages included the achievement of higher flux values of up to 50% as compared to a standard polyethersulfone UF membrane (100). The use of block copolymer thin films as a possible technique to overcome membrane fouling by proteins and other NOM was explored. The study showed that copolymer films that possess small and dispersed polymer blocks interacted unfavorably with the fouling species and showed an overall decrease in the permeate flux as compared with homopolymer films (101). There have also been a variety of hydrophilic monomers that have been grafted to membrane surfaces to increase their wettability and reduce their potential to foul during filtration. The monomers that have been employed include AA (75, 76, 81), methacrylic acid (MA) (74, 77, 78, 81, 102), vinyl acetate (VA) (98), NVP (44, 72, 82, 103, 104), glycidal methacrylate (GMA) (71, 98, 105), HEMA (73, 105), poly(ethylene glycol) methacrylate (PEG-MA) (77, 79–81,102), 3-sulfopropyl methacrylate (SPMA) (73, 78–81), 2-dimethyl amino-ethyl methacrylate (DAEMA) (102), 2-trimethylammonium-ethyl methacrylate chloride (AmEMA) (102), AMPS (80).

OPTIMIZATION OF OPERATING PARAMETERS/ CONDITION IN MEMBRANE FOULING CONTROL

The variation of operating parameters is one of the most sought after ways of reducing the fouling on membranes. Flow manipulation is the main focus of changing the operating parameters through inserts, turbulence promoters, increased flow rates, mixers, backflushing, pulsing, backflushing, high shear, pulsatile and reversal flow, vortex generation, gas sparging, force fields, ozonation, etc. These are some of the methods that have been employed as a means of reducing fouling on membranes and increasing permeate flux. Some of these methods such as vortex generation, air sparging, and shear induction have been developed to reduce the adverse effects of concentration polarization and membrane fouling. These phenomena are controlled by either increased shear at the membrane surface or the use of turbulence inducers. Increased shear is obtained by pumping the feed at higher flow rates or by using thin flow channels above the membrane surface. The superimposition of unsteady fluid instabilities on cross-flow improves the performance of membrane processes (106).

The effects of flow velocity and feed emulsion temperature on surface fouling of the membrane and permeate flux were studied and observations suggested that they were significant at higher emulsion concentrations and vice versa (107). Experimental results also showed that the permeability of the UF membranes could be recovered via a micellar solution of sodium dodecyl sulphate-pentan-1-ol-water. The modification of feed flow patterns in the improvements of permeate flux was also investigated (108, 109). A detailed study of the effects of operating parameters on flux in bubble-enhanced cross-flow microfiltration of baker's yeast suspension was carried out using tubular membrane (110). The study covered variation in feed suspension concentration, trans-membrane pressure (TMP), cross-flow velocity (feed) and gas superficial velocity. The same results of high flux enhancement with severe concentration polarization were obtained as well as the effectiveness of bubbling at low liquid flows. These results thus affirm that flux enhancement is definitely due to a disruption of the concentration polarization layer.

Fouling is also controlled by operating below the critical flux in the case of dye solutions and in the same way also investigated the effect of nanofiltration conditions (flow velocity, concentration, pH, and membrane precleaning) on the critical flux for mechanical pulp and paper mill effluents and model solutions for these effluents (111, 112). Authors illustrated the use of flow reversal to overcome permeate flux losses associated with concentration polarization and fouling and to enhance flux in UF. Laboratory scale tests using a hollow fiber module with BSA solution as feed showed that permeate flux was significantly improved under reversal flow conditions when compared with conventional unidirectional flow. The flux improvements were also observed to be very high with increased feed concentration and operating TMP (113).

The results from the experiments relating to the effects of an increasing shear rate at the membrane edge on reducing concentration polarization and on controlling membrane fouling during filtration of river water were discussed in (13). The effect of concentration polarization in NF and MF membranes can be reduced via an increase in the shear rate. This study also focused on increasing the back transport of particles away from the membrane by increasing the shear rate to attack the problem. The effects of shear rate on improving the removal of humic substances and controlling membrane fouling were also covered in the study. Water from the Chitose River was used as experimental raw water, and results indicated that humic substances were the major components of the natural organic matter in the water. A vibratory shear enhanced process (VSEP) was utilized for the treatment of the river water directly without incorporating any pretreatment (114). The overall conclusions and results showed that shear rate increment could effectively reduce the concentration polarization of humic substances in NF and MF membranes. It was justified via the increase in mass transfer coefficient and the reduction in the concentration on the membrane surface with an increasing shear rate. NF membrane fouling can also be alleviated and evaluated by the cake filtration model and controlled by the shear rate increase.

Turbulence inducers are used to create unsteady fluid instabilities, which induce turbulence via feed spacers and static mixers. These fluid instabilities have been used to disturb foulants, while channels with irregularities have been utilized in inducing mixing at the membrane/solution interface (115–118). Initial research to realize that fluid instabilities increased mass transfer away from the membrane was carried out (119).

The avoidance of fouling also results in easier cleaning of the membranes, which limits the severe cleaning procedures employed and subsequently prolongs the lifetime of polymeric membranes. With respect to new process plants employing membranes, the options for fouling abatement become more limited and the emphasis is geared toward physical and chemical methods. Some of these include prefiltration, the use of turbulence promoters, pulsed/reversed flow. Others include coagulation/flocculation, the use of antiscalants and surface modification.

An in-depth study (120) was carried out to determine the impact of various operating factors on membrane fouling in activated sludge membrane bioreactor (MBR). The various factors affecting the rate and extent of permeate flux decline were investigated and the operating parameters investigated included membrane types, module configurations, MLSS concentrations, suction pressures, and air scouring rates. UF and MF hollow fiber membranes made of the same material (polysulfone), submerged in the bioreactor, were used. Permeation results pertaining to this experimental approach showed that the rates of permeate flux decline increased with increasing membrane pore size. It was also concluded with respect to membranes that the decrease in permeate flux of size exclusion membranes is characterized by (i) short-term rapid flux decline, which is due to pore blocking and cake formation and (ii) long-term gradual flux due to cake compaction and irreversible fouling (121). It was also noticed that the rates of permeate flux decline increased with increasing TMP and initial operating flux (120). The experimental results showed that the permeate flux varied significantly according to the air blowing rate and the rate of permeate flux decline was reduced. This observation was due to an increase in back transport of foulants from the membrane surface by shearing stress at high air blowing rates (122, 123). The results also suggested that membrane performance was improved with intermittent suction and this is also due to enhanced back transport under pressure relaxation. The foulants that were deposited on the membrane surface were also removed efficiently by air bubbling under no pressure gradient across the membrane. This resulted in a lesser foulant accumulation rate (120).

The mode of fouling in the ultrafiltration of passion fruit juice and the effects of operating variables on permeation flux and resistances for UF of passion fruit juice were studied (124). The variations of permeation flux with respect to temperature and pressure showed that an increase in temperature from 30–40°C enhanced permeation flux due to an increase of mass transfer coefficient according to the film model. At 50°C, there was a drop in permeation flux due to the effect of an increased bulk viscosity and the probable formation of a true gel caused by cross-linking. This cross-linked gel subsequently increased the resistance to flow. At this temperature, a decline of flux occurred after a pressure of 117 kPa, which directly compares to a study on UF of pear juice. The study results showed that a polysulfone membrane was sensitive to fouling by passion fruit juice. It was also observed that the phenomena of flux decline during the ultrafiltration of passion fruit juice was very significant and on analysis of the foulant layer from this process, Yu et al. (125) found that pectin and sugars were the major components and that the remainder were cellulose, hemicellulose, and citric acid. The same conclusion was also derived when a similar experiment on Mandarin orange juice was carried out (126).

Other methods that have been employed to reduce membrane biofouling have included ozone and ultrasound. This was estimated via the growth of

Pseudomonas diminuta on modified polysulfone membranes. The important parameters that related to the successful dislodging of biofilm were ultrasound intensity, cleaning frequency, and distance from ultrasound transducer (127).

Backpulsing/Backflushing/Backwashing

This is a common method of reduction of membrane fouling employed in cross-flow filtration processes. Cross-flow filtration techniques and membrane technologies have been employed on a global scale for the removal of particles, colloidal species, and microorganisms but the principal limitation lies in the flux decline associated with particle formation on the membrane, thus hindering mass transfer. Backflush was used to eliminate particle deposition, which allowed efficient flux recovery. In microfiltration, high feed/retentate velocities are used to reduce cake formation and concentration polarization. It is a common practice to pump filtrate back through the membrane into the feed channel to give a periodic backwash. This lifts the deposited material off the surface of the membrane. The backwash pressures need to be greater than the operating filtration pressure. The efficiency and effectiveness of this technique is limited to surface deposits removal from the membrane. It becomes effective with strong adhesion of deposits and if there is any pore fouling (6). Periodic backwashing improves membrane permeability and reduces fouling, thus leading to optimal, stable hydraulic operating conditions. Air backwashing in submerged membrane reactors can increase the flux up to fivefold (128).

When the technique is carried out at a faster rate, it is known as backpulsing or backshocking. Backpulsing is a cyclic process of forward filtration followed by reverse filtration. Reversal filtration involves reversal of the flow through the membrane by changing the orientation of the TMP (2). More rapid backwashing has been claimed to be more effective and backpulses are of short duration and may be operated continuously or periodically. They are particularly effective with colloidal suspensions and with streams requiring protein transmissions through the membrane (129–131). The backpressure is applied in an extremely rapid pulse every few seconds throughout the process. The reverse flow removes the particles that are reversibly deposited on or within the pores of the membrane, while the foulants are swept off the membrane via the cross-flow. These actions subsequently reduce fouling and improve permeate flux over time (2). Cross-flow filtration with rapid backpulsing has been studied in-depth by a number of groups in varying membrane/foulant system, who documented the method as an effective means of controlling fouling and increasing permeate flux for nonadhesive foulants exhibiting reversible fouling (130, 132–136). The use of rapid backpulsing was also studied extensively (130, 132, 133, 137, 138).

A combination of backpulsing and membrane surface modification for the reduction of membrane fouling was investigated, and it involved employing a novel photoinduced grafting method to render polypropylene (PP) membranes hydrophilic (7). The membranes were rendered with neutral or positively or negatively charged surfaces by grafting monomers of PEG200MA, DMAEMA, or AA, respectively. The scope of the experiments carried out involved the use of three membranes; unmodified, modified, and commercial membranes (CA). They were employed in a cross-flow microfiltration system with and without backpulsing and also in the presence of *Escherichia coli* bacterial suspensions. It was also expected that reversible and irreversible fouling could be reduced by the combination of backpulsing and membrane surface modification. The results obtained in the experiments showed that without backpulsing, the permeate volume achieved was almost identical for the different membranes but with backpulsing, significant improvements in permeate volume were observed in the case of the modified membrane surfaces. This was especially for low feed concentrations and short filtration times. An example of the validity of the results showed that the permeate volume with backpulsing was highest for the neutral, hydrophilically modified PP membrane and for the commercial CA membrane, approximately 2.6 times that of the unmodified membrane without backpulsing. Also, the pure buffer flux that was recovered after backwashing the fouled membranes for an extended period was twice as high for the neutral hydrophilic membranes as it was for unmodified hydrophobic PP membranes. Backpulsing is used with liquid and gas phase reversal flow. With liquid phase permeate is forced back through the membrane by the reverse transmembrane pressure (139). Alternatively, in gas backpulsing different gases can be used for their periodic pulsing through the membrane from the permeate side (140). The use of backwashing with a fluid or a gas was also shown to be effective (141).

Rapid water backpulsing, gas backpulsing, and crossflushing were also evaluated for their ability to reduce membrane fouling and concluded that the recovered permeate volumes were approximately twice as high for filtration with backpulsing as they were without backpulsing (2). This demonstrated that backpulsing is effective for the enhancement of permeate flux with or without internal fouling. However, the results also indicated that the recovered flux of a membrane fouled with backpulsing after a long backwash was lower than that of a fouled membrane without backpulsing, indicating that more internal fouling occurs when backpulsing was used to periodically remove the external cake layer. This also shows that internal foulants are not removed as efficiently as external foulants by flow reversal through the membrane. The combination of backpulsing and surface modification thus demonstrated an effective method in reducing both adhesive and nonadhesive fouling.

This study (142) focused on membrane recovery of light nonaqueous phase liquids (LNAPLs) and the mitigation of fouling through backpulsing with experiments through the extraction of kerosene, diesel fuel, and LNAPLs showing the presence of suspended solids in LNAPLs. Membrane fouling was observed in the experiments due to pore blockage, pore constriction, and cake formation. Backpulsing was found to mitigate these causes and improved recovery rates up to 30% over a 15 h period but was not necessarily ideal for the prevention and control of irreversible fouling.

Pulsing

The use of pulsatile flow has been geared toward producing oscillations and unsteady flows. They are obtained by introducing pulsations into the feed or filtrate and permeate channels (6). The filtration performance of yeast cell harvesting was reported to have greatly improved via oscillatory flow mixing in both tubular and flat sheet membranes. The additional benefit of implementing the method was an increase of about sevenfold on the flux but investigations are still in progress to measure the effects of frequency and amplitude (143, 144). Researchers reportedly observed approximately 300% increase in flux improvements when they utilized periodically spaced, doughnut-shaped baffles in UF tubes and pulse flows. Pulsing the flow increased the flux by a further 50% (145, 146), and 20% when using tangential inlet ports to induce helical flow (147).

A variation of the pulsating flow technique was also investigated using an intermittent jet of fluid at the inlet to a tubular filter and fluxes up to 2.5 times were realized, which were higher than those obtained without jets (148). It was also reported that a further variation of the pulsating flow technique using a flexible tube at the inlet to a ceramic with the tube subjected to alternating pressure was possible. Flux increases were gained up to 60% (149). Authors have also looked into utilizing a periodically spaced baffle with pulsatile flow, with results indicating that the combination produced significant enhanced microfiltration. Other researchers have confirmed the effectiveness of pulsatile flow techniques for improving permeate flux by the use of a rotating perforated disc placed in front of the entry section of a bundle of tubular membranes (130, 150–154). This created a temporary increase in velocity in the various tubes. It was also illustrated that the pulsatile flow rate increased the wall shear rate as velocity increased at high frequencies (106). Another technique that was assessed was the Airflush technique, which involves an intermittent two-phase flush through the tube to dislodge and remove the cake. It was found to be a lot more efficient than a single-phase liquid flush (155).

Turbulence Promoters/Vortex Promotion/Shear Stress

The use of turbulence is one of the many methods that have been used to reduce the degree and presence of fouling on the surface of the membranes. Various methods utilized the alteration of the hydrodynamics of the fluid. The hydrodynamic methods include the use of inserts that act as turbulence promoters. The inserts encourage turbulence as the fluid flows over them, causing instabilities. The inserts or turbulence promoters come in many shapes and sizes including static rods, metal grills, cone shape inserts, spiral wire, and disc and doughnut-shaped inserts. They also produce vortices, which promote good mixing of the fluids and minimizes concentration polarization effects (8). Incorporating the use of baffles in a tubular membrane, which can create a secondary flow, fluid instabilities, and local increase of the velocity was found to also increase turbulence (156). Figure 4 shows a helical baffle incorporated in a tubular membrane.

There was also a comparison of several possible methods for flux improvement for a fine chemical nanofiltration process. The investigated techniques included the use of higher cross-flow velocities, reduction of pressure drop across the membrane module, the use of turbulence promoters, and of vibrating membranes (VSEP system) (157). An example of achieving turbulence involves the use of high cross-flow, rotating membranes, and helical inserts. Helical screw threads are semicircular in shape to permit approximately half the flow to pass along the helical path (158).

A high shear stress is also achievable at the membrane surface via these turbulence promoters and by rotating the surface at high speed, rather than pumping the feed across the surface at a high cross-flow velocity. Varying the rotational speed of the rotating elements and the Taylor vortices that are created in the filters can vary the magnitude of the shear stress and create an added stress, which limits the build up of deposits at the surface. The in-depth study of the use of curved channels to produce Taylor or Dean vortices was carried out by designing a curved channel duct to generate dean vortices as a result of flow around 180° curves (117). The authors provided evidence to prove the existence of vortices in the curved region and flat sections. They also reported an increase in permeation rates up to 30% in the presence of weak dean vortices as compared to pure cross-flow. Dean vortex microfiltration was also utilized using controlled centrifugal instabilities for the microfiltration of feeds containing cell and homogenate suspensions. Flux improvements of up to 70% were reported in the helical modules compared without the helical parts (159). The use of Taylor and Dean instabilities in boundary layers along curved walls to enhance cross-flow performance was reviewed while authors also reported the utilization of intermittently operated microfiltration. The former used $Mg(OH)_2$

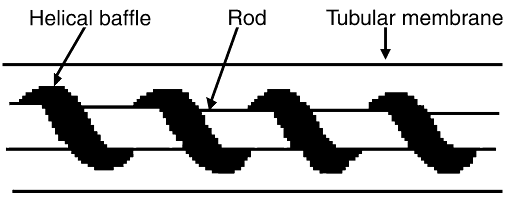

Figure 4. Schematic diagram of a helical baffle inserted in a tubular membrane (8).

slurries in periodic operation with filtration and cleaning stages. The results indicated that such a procedure could increase permeate production as long as it was reversible fouling occurred. The latter developed a theoretical optimization of a dead-end filtration with a periodic backwash to remove the deposited cake and restore the permeate flux (160, 161). The advantages of this intermittent technique over the pulsatile flow technique include its offer of independent control over the permeation and cleaning phases. This method was also implemented without prior knowledge and understanding of the fouling mechanisms, except that the deposited cake was irreversibly compressible and that a shear stress could remove it (162). A method was developed that could be regarded as a low-frequency alternative to pulsatile flow, which produced periodic bursts of velocity and pressure along the membrane at frequencies of up to 1 Hz (163).

Dean vortices were used in tubular nanofiltration modules for subsequent studies on depolarization of dilute and concentrated salt solutions, and on defouling of salt solutions containing suspended silica particles (164). The effects of turbulence on cross-flow microfiltration were studied experimentally, and flux enhancements of more than 500% were achieved. There were also flux improvements over 300%, for hydraulic dissipated power in the range from 0.13–0.95 W, which indicated that the use of turbulence promoters is more energy efficient than operation without their use. They also caused large scouring of the membrane surface and provided a significant reduction in reversible fouling. The membrane cleaning efficiency was subsequently improved compared to the experiments without promoters (165).

The research presented in (166) focused on the use of a dispersed phase to disrupt concentration polarization, and it was concluded that the dispersed phase affected the control of eddy sizes and formation as well as the rate of energy dissipation in the fluid. The other reasons for the study were to investigate the turbulent intensity, the effect that a void fraction would have on the dispersed phase, and the stress that will be produced on the behavior of concentration polarization. The dispersed phase acted simply as a turbulence promoter and the experiments were carried out on the basis of UF, which occurred in a gelatin solution in the presence of steel balls, and the predicted results were compared and found to be similar to those obtained by Rios et al. (167). The experimental results showed that the favorable conditions for mass transfer increments were realized for smaller eddies and high energy rates. Concentration polarization in a membrane tube can be controlled by the placement of inert solid particles as a dispersed phase in UF experiments (166, 167).

The use of helical baffles in the clarification of highly charged wine increased the permeate flux from $10\,L/h \cdot m^2$ to $25\,L/h \cdot m^2$. There was also the chance of a further 200% increase with the same dissipated power used (168). The purpose of the research was to determine the efficiency of using helical baffles of different turns per 50 mm length by winding a metal wire onto a metal rod, which is placed centrally in the module. Tubular modules were used in this study and the optimum configurations of helical baffles geometry-wise were explored. It also documented the use of turbulence promoters or inserts in the tubular membranes, which exist as static rods, metal grills, cone-shaped inserts, doughnut shapes, among others. Permeate flux improvements increased over time in comparison to those obtained without baffles. As the numbers of turns increased from 1 turn per 50 mm to 4 turns per 50 mm, an increase in permeate flux was recorded, but further increments made flux decrease as shown in Figs. 5 and 6. From the experiments, it was shown that a helical baffle made up of 4 turns per 50 mm baffle length is optimum. The experiment's credibility is undermined as the procedures are restricted to smaller pipe diameters and so the fluid dynamics are distorted and tampered. This is in contradiction to the initial objective of retaining the properties of the liquid (8).

A review on the detailed experimental study of the performance of helical screw-thread inserts in tubular membranes was shown elsewhere (169). The study was designed to investigate the detailed fluid dynamic processes contributing to flux enhancement when screw thread inserts were used in tubular membranes. The membranes that were fitted with inserts were tested under MF, UF, and NF conditions. The inserts were tested under microfiltration conditions using yeast solutions, under ultrafiltration conditions using reconstituted powdered milk solutions and under nanofiltration conditions using synthetic dyes. The study also included the "gap analysis" of plain membranes and membranes fitted with inserts. The behavior of the screw thread inserts were modeled using computational fluid dynamics (CFD). This study reported that helical inserts offer particular advantages for the treatment of delicate, high-value products such as pharmaceuticals or in bioprocessing. Short tube lengths (up to 1 m) ensured that the pressure drop along the channel could be kept low enough to avoid damage to delicate fluids. The permeation tests under all the conditions showed dramatic and significant rises in permeate fluxes by factors of up to 10 when inserts were compared with plain membranes at the same cross-flow rate. The inserts also had higher-pressure drops than the plain membranes under the same

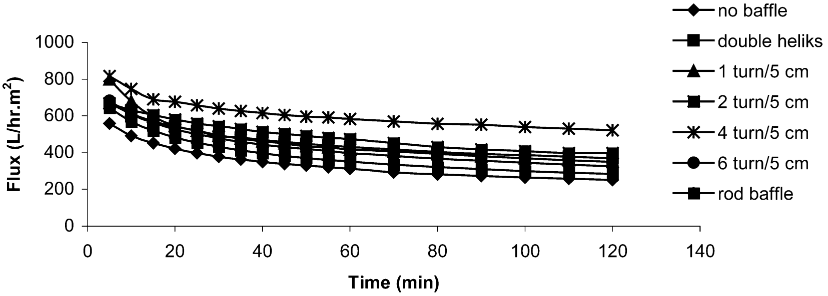

Figure 5. Flux performance of different types of baffles at 1.361 atm (TiO_2) (8).

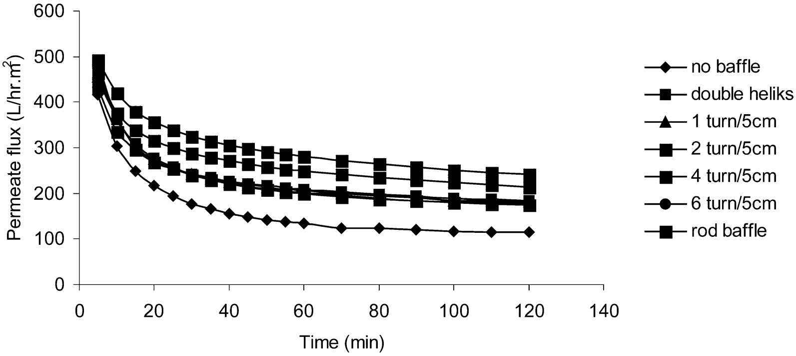

Figure 6. Flux performance with baffle/without baffle of 1 g/L TiO_2 (1.361 tm) (8).

conditions. The helical inserts in comparison to plain rod inserts showed higher fluxes with lower pressure drops. The ability of the inserts in improving MF fluxes in handling biological fluids was demonstrated. There was the problem of membrane damage by insert vibration but it was attributed to the reciprocating pump that was used in the rig, rather than being hydrodynamically induced by the presence of the insert. The mitigation method was to fit rubber spacers, which proved to be better.

A detailed study of observing the flux decline phenomena using a dye solution at high concentration in the laminar flow region was carried out (170). The authors used thin wires as turbulent promoters in order to enhance the flux. The experiments with turbulent promoters were conducted at the same operating conditions as those without promoters. The authors documented that the use of thin wires as turbulence promoters had never been discussed in preceding literature reviews. Sixteen equispaced thin wires of 0.19 mm diameter were placed laterally in between two neoprene rubber gaskets as turbulent promoters. The presence of wire resulted in an increase of local velocity at the vicinity of the wire, with an increase in Reynolds number of approximately 50%. This subsequently led to turbulence increase and flux increase. The membrane was also washed with distilled water in between runs and kept in 1% surfactant (Sodium dodecyl sulfate [SDS] solution) for about an hour. The surfactant has the ability to form micelles with adsorbed dye materials and they help to remove the dye from the membrane skin. This led to a considerable increase in permeability. The results showed that at the operating conditions used in the experiments, there were increments in permeate flux within the range of 20–102% using the turbulent promoters. This occurred due to the turbulence created by the promoters, which make the deposited layer of the solute unstable over the membrane surface. The promoters enhanced the mass transfer of solute from the surface to the bulk solution, leading to an increase in flux. It also reduced the concentration polarization, resulting in less solute deposition over the membrane surface. It becomes more pronounced at higher velocities. The overall economic viability of this process is hence justified, and it was also observed that the significant flux enhancement in the range of 40–100% was achieved while the retention of dye remained unchanged.

Belfort et al. (171) illustrated a number of ways in which the fluid mechanics design has been utilized in the improvement of permeate fluxes, and Kroner et al. (172) used a rotating filter as one wall of an annulus in which Taylor vortices were formed. These sets of experiments demonstrated flux enhancements by a factor of three when compared to conventional cross-flow microfiltration of microbial suspensions. An insight into the use of flat membranes with dimpled surfaces to separate blood plasma was achieved in (173). The developed vortices were introduced into the flow channel via oscillation of the flow. This showed an improvement of fivefold on the flux. Descriptions of the designs of tubular membranes with screw thread inserts were detailed with a corkscrew vortex implanted on the helical flow, which caused radial mixing.

The development of membrane modules to include turbulent promoters and inserts to induce mixing, backpulsing, and fluid instabilities has been introduced into the membrane processes to improve mass transfer at membrane surfaces as reported in (174). The principal purposes of the coupled components are to increase back-migration of solute to the bulk flow region and also to limit the growth of the particle layer deposited on the membrane. Hollow fiber membranes as turbulence promoters were investigated by placing them perpendicular to the feed stream. A similar method was then studied where tests were carried out on the axial flow hollow fiber modules of various packing densities (175, 176). Research on the use of turbulence promoters was studied to combat the problem of flux decline via screw-threaded inserts and oscillatory flow in a tubular module, with bovine blood used as a working fluid (177). The rate of protein recovery was close to 100% with enhanced permeate flux (fivefold) using a longer piston stoke. The overall performance of the process was analyzed with the effects of pulsation frequency and piston stoke length, and membranes of 0.2 and 0.45 microns were utilized. The experimental results proved the invaluable benefit of oscillatory flow when applied to a tubular membrane module equipped with a helical insert.

Oscillatory flow rather than steady flow was used in the enhancement of the mass transfer rate of the process, and the concept of vortex mixing in dimpled membranes was studied (178–181). It was reported that a vast improvement in flux enhancement was achieved when compared with steady flow operation. One of the major problems with microfilters that were operated in laminar flow to avoid cell damage was the poor filtration efficiency. The effective method used to counter this was the use of a tubular filter with a loose-fitting helical insert to filter blood in steady flow (182). Helical screw thread inserts were used in the UF of bovine serum albumin (183). The inserts were compared to plain rod performances and at flow rates up to 0.41 L/min, the helical insert produced significant enhancement of permeate flux. Other work in this area was illustrated in nanofiltration trials using dyes with a membrane that was fitted with a helical insert and operated at a mean flow rate of 9 L/min; TMP of 5–30 bar. It consistently gave higher permeate fluxes than those from a corresponding plain membrane operated at twice the flow rate.

Another investigation involved the development and use of a new vortex-flow membrane module with glass balls to enhance permeates flux through a flat sheet membrane. The effects of the operating parameters on the microfiltration of an oil-in-water emulsion were investigated. The results of the investigation showed that permeate flux was observed to increase with the feed flow due to the presence of glass balls. A significant flux increase was gained with the presence of glass balls when compared to the case without glass balls. It was observed that the flux enhancement was significant when the feed emulsion was highly concentrated, thus indicating that the mechanism of this enhancement was to disrupt the concentration boundary layer and subsequently reduce the presence of fouling (184).

Gas Sparging/Air Sparging/Bubbles

The use of air or other gases to create a two-phase flow within the tubular membranes has been continually explored recently as a very effective means of fouling reduction and permeate flux enhancement. Air sparging generally consists of generating an intermittent gas/liquid two-phase flow by injecting air directly in the concentrate compartment during the filtration process. It has also been shown to be very efficient with hollow fiber membranes and tubular membranes for *Escherichia coli* suspensions (111). It is very useful in significantly improving the flux in UF and MF for numerous applications, especially in the case of solutes or particles in water. However, this technique is not as effective as the use of turbulence promoters above due to the problem of handling the gas injected into the membrane (6).

The process of injecting air into the feed stream in order to reduce the presence of particle membrane fouling in organic hollow fibers has been studied extensively and the efficiency of a two-phase flow was evaluated to prevent the formation of a cake layer; while the effects of air injection on permeate flux at different velocities was examined (185). The results obtained showed that the permeate flux without injecting air in the feed stream decreased with time but during the first few minutes, the permeate flux experienced a sharp decrease due to particle deposit formation, thus the added flow resistance. On the other hand, permeate flux with air injection decreased, but at a lesser rate. The permeate flux was also maintained at a higher level when the air velocity was higher. Further results proved that increasing the air velocity leads to the formation of a particle deposit with less mass transfer resistance. Also, an intermittent gas flow seems less effective than a steady one in similar experimental operations. It was reported that there is the evidence of alteration of cake structure or fouling layer with the application of gas sparging to the MF of particles. This affects its specific resistance by reducing it (185). Improved fluxes over time were due to changes in the cake structure with the gas-sparged ultrafiltration of clay suspension.

The effects of air injections into the feed side of flat sheet membrane modules on permeate flux and protein transmission were examined using four protein solutions, human serum albumin (HSA), human immunoglobulin G (IgG), bovine serum albumin (BSA), and lysozyme (Lys) as test media (186). Polysulphone and polyether sulphone were the two membranes used with results showing that gas sparging increased permeate flux by up to 50% but protein transmission was reduced significantly. It was earlier discovered that at a low transmembrane pressure $\sim$50 kPa, with a mixture of BSA and Lys, the injection of gas increased permeate flux by only 10% but had a more convincing effect on protein fractionation. The permeate flux increased by between 60–270% due to gas sparging was achieved in other research on ultrafiltration of BSA, dextran solutions and also in the microfiltration of yeast suspensions using tubular membranes (187–191).

A method of introducing gas into the feed stream as a means of breaking up the dense cake layer on the surface of the membrane was examined using gas-liquid two-phase cross-flow ultrafiltration in the downward flow condition with a tubular membrane module (192). The module was installed vertically, with the feed solution and gas bubbles flowing downward in the membrane. The permeate flux realized in this operation was compared with that in conventional single-phase UF and gas sparged upward cross-flow operations. The operating parameters that were examined with dextran solutions included liquid flows, gas flows, TMP, and feed concentrations. The results showed a significant increase in permeate flux of 320%. It was observed that the addition of gas led to significant enhancements in flux for upward and downward flows. This proved the technique to be efficient in preventing concentration polarization and disrupting any that was present. Flux enhancement was more pronounced when the concentration polarization was very severe, further indicating the validity of the disruption. The use of a low flowrate gas sparging enhanced UF while the introduction of the bubbles promoted an early transition from laminar to turbulent. The bubbles could act as stationary or slow-moving baffles to further reduce the gas flowrate, depending on the process conditions.

Air sparging as a technique used to improve backwashing efficiency in a dead-end fiber module was studied and proved effective for the detachment of the cake layer formed during the filtration of bentonite suspensions (193). The efficiency of the rinse phase was also improved considerably on the introduction of air, acting as a piston to flush out the major part of the free volume in the module. The combination of air sparging and backshock thus improves the productivity since less permeate is consumed during backwash. On the other hand, the flux decline caused by membrane fouling often cannot be fully replenished via gas sparging probably because internal pore fouling is not reversed by surface shear. Thus, bubbling or gas sparging can be efficiently applied to membrane processes, especially MF and UF processes. It can also be utilized within membrane modules or in submerged systems as they have been proved to achieve the desired or improved flux rates and enhanced fouling reduction immensely.

The performance of air sparging was tested on a submerged MBR for wastewater treatment with emphasis on two techniques. The first involved the use of air injection into membrane tube channels to enable circulation of mixed liquor in the bioreactor, and the second used periodic air jets into the membrane tube. Results observed showed that the cake layer was removed sufficiently due to air injection.

Another application of the use of air sparging for flux enhancement in nanofiltration membranes was investigated using droplet suspensions in water (11). The process was tested using flat sheet membranes for two types of feed: stabilized and nonstabilized oil-in-water emulsions The focus of the study was based on an industrial application of NF membranes, including treatment of cutting oil fluids, which are encountered in metal manufacturing, metal working, and processing. The tasks are the separation of the oily dispersed phase and the removal of the dissolved organic compounds from the aqueous phase. These sets of experiments were carried out in order to meet two main objectives: to obtain an oily phase as concentrated in oil as possible in order to be able to reuse the oil; to obtain an aqueous phase in accordance with the regulation levels for industrial wastewater.

The initial results of the experiments showed that the injection of air, even at very high velocities, did not modify the permeability to pure water. Air sparging with nonstabilized oil-in-water emulsions also showed lower filtration ability because of the formation of an oil layer at the membrane surface as the hydrophobicity of the membrane increases in the absence of surfactants. It was observed that in both of the cases, a significant increase in permeate flux was reached with air sparging. This was a result of the ability of air bubbles for disrupting the oil layer over the membrane surface. Air sparging has also been shown to be effective and efficient with hollow fiber membranes and also with tubular membranes for *E. coli* suspensions, dextran or albumin solutions (194), clay suspensions, clay particles (195, 196), and natural surface waters (197).

Bubbling

MBR is an innovative technology in which gravity settling of the activated sludge system is replaced by a membrane separation process such as MF or UF. This has gained widespread acknowledgment as an advanced treatment alternative, although the acceptance is still limited due to the problem of membrane fouling via accumulation of various foulants within the membrane pores and onto the membrane surfaces (198). It was demonstrated that the degree of membrane fouling in the MBR process using UF membranes was caused by such factors as soluble chemical oxygen demand (COD), mixed liquor suspended solids (MLSS) concentration, and the viscosity of the activated sludge suspension. An increase in the permeate flux decline with increasing solid retention time was observed showing the relationship between MLSS concentration and membrane fouling (199, 200). A drastic decline in membrane permeability during MBR operation was attributed to the formation of cake layer on the membrane surface, mainly consisting of bacterial cells and bacterial extracellular polymers (EPS) (201). The severity of membrane fouling is determined by the combined effect of various physical, chemical, and biological operating factors, and it was confirmed that in order to maintain a permeate flux during operation; the cake layer deposited on the membrane surface needed to be removed by a shear. This can be created by various means and is implemented in an MBR by causing a shearing stress through uplifting air bubbles (180).

The MBR has been developed over the last decade into commercially available equipment and the main challenge has been membrane fouling and bubbling, which has a very important role in its control. A typical MBR comprises 50% airflow for aeration purposes and another 50% for the control of fouling. According to the literature concerning submerged systems that employ bubbling, colloidal, and soluble fractions are the main contributors to fouling in membranes (202–204). A good control strategy for fouling caused by mixed liquor is through optimizing system design and operation. The majority of systems employ controlled flux, intermittent suction and backwashing, with the suction providing the opportunity for bubbling to prevent the fouling during a zero flux period. Coarse bubbling is another method used for the control of fouling (205).

The cleaning of the membranes regularly protects the membrane from becoming susceptible to fouling, and several studies relate to cleaning as the sparging of air into the retentate sides of the membrane module with and without combining a reversed permeate flow (193, 206–208). Various techniques have been used to reduce membrane fouling, and in submerged membrane bioreactors, air bubbles can prevent the deposit forming on the membrane surface (209–213). A comprehensive review of the detailed applications of the technique of applying gas bubbles and slugs in microfiltration and ultrafiltration was studied with flow inside tubes and fibers and across flat sheets, etc. The principle of induced shear is reported as a major strategy in controlling concentration polarization and subsequent fouling (214). The addition of other media, including solids (ballotini), was studied and this principle was based on two-phase flow to disturb the boundary layer. The limiting factor here is that the solids being introduced could inadvertently cause significant damage to the membrane (215). Gas bubbles were found to be ideal as a second phase and they posed lesser risks to the membrane and are easily separated from the process stream (214).

With respect to nanofiltration, there have not been many reports that quantify permeate flux enhancement in tubular membranes using gas bubbles. Flux enhancement in other membrane modules have been investigated by a number of researchers who conducted experiments using flat sheet membranes. They utilized the principle of entrapping bubbles in enhancing the diafiltration of bacteria suspensions using both flat sheet membrane systems and other membranes (189). Permeate flux was improved by approximately 100% with the use of a 300 kDa PS UF membrane and by 30% with the use of a 0.2 mm MF membrane. With respect to ultrafiltration and flux enhancement, gas sparging effects on permeate flux have been experimentally assessed over a range of operating conditions which include dextrans, enzymes, BSA, and cells as the test media. Membrane orientation and the effects on flux and fouling have been extensively studied with respect to vertical and horizontal orientation. The experiments involving the use of dextran as a test medium, with a single-phase flow showed that by injecting gas bubbles at very low flow rates, there was a significant increase (214). There was no apparent increase in flux with a higher flowrate though.

Orientation is very important for tubular systems and the results obtained indicate that permeate flux is higher in a vertical tubular membrane module with an upward flow as shown in Figs. 7 and 8. When all parameters are the same, the values are in descending order, vertical downward flow, vertical upward flow, and horizontal flow (214). This ties in with some work done, which studied the effects of the mounting angle vs. flux enhancement and reported that a 50° inclination angle produced the maximum flux enhancement (215). Cheng et al. (216, 217) carried out some work on boundary layer resistance and came to a conclusion that the same permeate flux achievable in a single-phase UF, coupled with a high cross-flow

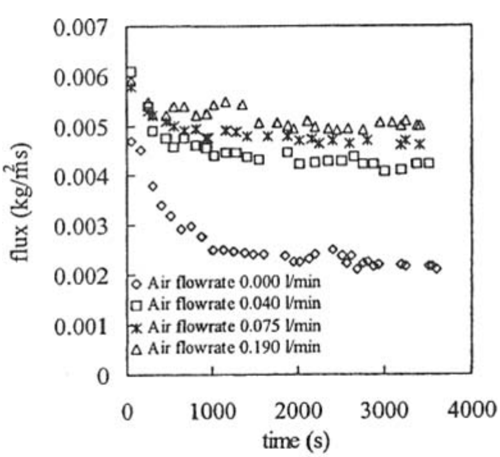

Figure 7. Effect of gas sparging on permeate flux (vertical tube UF of dextran) (240).

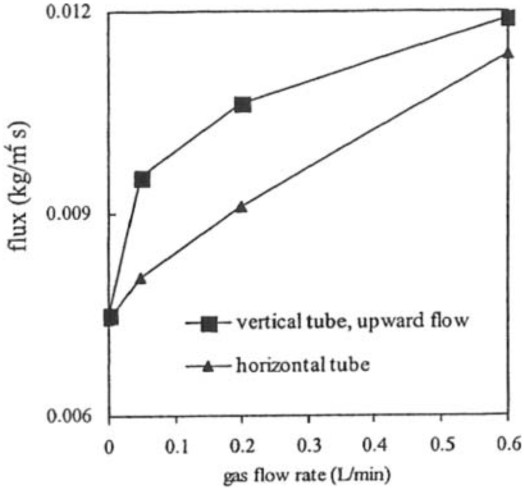

Figure 8. Effect of tube orientation on gas sparged UF (214).

velocity can be achieved with a lower liquid velocity via the addition of gas slugs of moderate velocity. Gas sparging is thus an efficient method of disruption of concentration polarization.

A proposal was put forward to develop a gas-liquid two-phase cross-flow microfiltration process coupled with a digester. The methane gas that was generated was used to introduce air into the system. This was in direct alignment with the realization that the injection of gas to create a gas-liquid two-phase flow controls cake formation and enhances flux efficiently (218, 219). Mercier-Bonin et al. (220) used flat sheet membranes to the effect of gas bubbles on permeate flux in yeast MF and they reported a fourfold flux increase. They also found that by comparing vertically and horizontally installed modules, the flux improvements were higher in horizontal modules, as opposed to the reverse in the case of tubular modules. With respect to hollow fibers, the first recorded attempt at utilizing bubbles to enhance membrane filtration was carried out using entrapped bubbles for diafiltration of 1% *E.coli* suspension and reached up to 65% flux improvements (221). In subsequent work carried out in the same area, the same pattern of results emerge and the conclusion is that the flux enhancement due to bubbling appears less significant than in tubular or flat sheet modules. It was also suggested that this was due to high shear in hollow fiber modules for concentration polarization control.

Additional Force Fields

A number of alternative forces can be used in principle to enhance the performance of microfiltration and also to reduce the effects of fouling due to charge interactions between charged solutes and the membrane. Electro-ultrafiltration is a technique developed to combat residual cake formation at the membrane surface by the use of an applied electric field. In this process, the imposed electrophoretic force limits the accumulation of the solutes on the membrane surface. The permeation rate is also enhanced through the filter cake due to electro-osmosis as a secondary electrokinetic phenomenon (222).

The use of electric fields among alternative force fields has been employed and studied to reduce the problem of fouling due to charge interactions between charged solutes and the membrane. The convective flow of the solutes can be equalized to a greater or lesser extent by giving an electrophoretic velocity to the particles via an application of a d.c. electric field gradient. The extent of membrane fouling can thus be reduced by this means, which would enhance the resulting permeate flux (6). On the other hand, greater flux enhancements are possible when using steeper field gradients but the downside to using d.c. electric fields are gas evolution by electrolysis. The benefits of using this method include the fact that low crossflow velocities may be used in an industrial context whilst utilizing this method. They could be as low as 0.1 m/s. This directly reduces the pumping costs, heat inputs, and improved shear streams. However, the corrosion of electrodes and power consumption to an extent has limited the successful commercialization of this process. These problems associated with the above process can be reduced via pulsing the electric field, which is achieved by intermittently applying a potential at intervals (6).

The use of an electric field has also been shown to be efficient to avoid fouling phenomenon and to increase the permeate flux in the case of a synthetic dye solution (223). Researchers made use of stainless steel microfilters, which doubled as a filter and a cathode, and applied the potential continuously. After this development, Bowen et al. (224) illustrated the fact that the possible electrolysis of the feed liquid was a suitable mechanism for the reduction of fouling. This involved evolving hydrogen gas at the cathode to cause a continual dispersion of the material that was deposited. Bowen et al. introduced short pulses of electric field in order to scatter the deposits that accumulated on the electrically conductive membranes (224, 225).

The principle of applying electrophoretic and electro-osmosis effects via the introduction of an electric field to reduce the effect of membrane fouling was explored in ultrafiltration of protein solutions (222). The effects of a superimposed electric field on the characteristics of dead end inclined and downward ultrafiltration of BSA solution. The method used in this experiment was electro-ultrafiltration. After the experiments involving both the inclined and downward UF were carried out, the flux difference variations between the two methods were examined and the range of application was estimated by the introduction of critical electric field strength. Subsequently, a mathematical model was further developed to describe permeate flux and its calculations were in agreement with the experimental information.

Other methods of electrically enhanced filtration have also been discussed in research papers over the years (226–231). The convective flow of the solutes or particles can be counterbalanced to a greater or lesser extent by giving an electrophoretic velocity to the particles through the application of a d.c. electric field gradient. The contribution of fine particles and colloids to membrane fouling can be reduced. The degree of flux enhancements is dependent primarily on solute molecule or particle size, surface charge, and the magnitude of the imposed field gradient. The disadvantage of using d.c. electric field is gas evolution by electrolysis (225, 229). With respect to pulsed electric fields, the power consumption and other problems associated with continuously applied electric fields can be reduced by pulsing the electric field; the pulsing may be achieved by switching the applied potential on and off at regular/irregular intervals (229).

The use of ultrasonic fields have been researched as well in reducing fouling on membranes. The passage of ultrasound waves through a suspension can cause particle dispersion, reduction in viscosity, changes in particle surface properties, and cavitation. Even though dispersion can potentially increase the fouling rate due to the formation of higher resistance membrane deposits, the combination of cavitation and relative movement between the solid and liquid phases is responsible for permeation enhancements (6). The permeate flux can be markedly increased by the simultaneous addition of electric and ultrasound fields. Both of the fields are seen to reduce fouling when applied individually, but the extent of improvement by the ultrasonic field can be minimal (6).

CLEANING PROCEDURES

This is a very important step in the regeneration of the membranes, and the fouled membranes are commonly rejuvenated by cleaning-in-place (CIP) procedures. They involve shorter downtimes than cleaning-out-of-place (COP). CIP may or may not involve external chemicals. In the case of not involving chemicals, a periodic reversal in flow direction may help in the prevention of particulates from clogging the module inlet, or a periodic backflushing of the membrane via reverse flow of permeate can be an effective way to remove surface foulants from the membrane (6). Surfactants decrease the surface tension of the solutions that are in contact with membranes. They are known to improve the hydrophilicity of hydrophobic membranes. Therefore, they are expected to have acceptable results as a cleaning agent (232). Air has also been used periodically during membrane cleaning in capillary or tubular ultrafiltration membranes. Intermittent forward flushing with air also allowed the removal of the deposits from the membrane surface for municipal wastewater treatment (233). Cleaning usually performs in three different forms; physical, chemical, and biological. The first step of chemical washing is to find appropriate materials as cleaning agents (234). The choice of the best materials depend on feed composition and precipitated layers on the membrane surface and in most cases is performed by trial and error (235). The choice of cleaning solution is not only determined by the foulant type, but also by the compatibility of the membrane with the solution at the cleaning temperature (6).

The use of an inappropriate cleaning agent could adversely affect performance of the membrane (236). The selected materials should be chemically stable, safe, cheap, and washable with water. They must also be able to dissolve most of the precipitated materials on the surface without damaging the surface (237, 238). The permeate flux caused by irreversible fouling can be recovered only by chemical cleaning and/or mechanical backwashing (239). The cleaning agents are acids, bases, enzymes, surfactants, and disinfectants and combined cleaning materials (240). Disinfectants or other cleaning chemicals have been used and utilized together with physical methods such as air and liquid backwashing to fully recover membrane flux (241–243). Daufin et al. (244) considered the use of a one-base washing step followed by an acid step to clean membranes that were fouled with milk and whey while better results were proposed via a one-enzyme washing step followed by chemical washing. While using the materials, the operating parameters like pH, concentration, velocity, pressure, and temperature are also considered. Also, the periodic reductions in feed pressure while maintaining a high cross-flow can help to control gel layer growth (245).

A cleaning agent can affect fouling material present on a membrane surface in three ways: (i) removal of the foulants; (ii) changing morphology of the foulants, e.g., by swelling or compaction; (iii) alteration of surface chemistry of the deposit so that the hydrophobicity or charge is modified (246, 247). The related in situ cleaning method with respect to backpulsing is the cross-flushing method. This is accomplished by maintaining flow over the membrane while periodically stopping the permeate flow, thereby eliminating the pressure drop across the membrane and allowing the shear exerted by the cross-flow to erode the foulant. The process of cross-flushing is relatively simple compared with water or gas backpulsing due to the fact that it does not require a pressurized tank or pump for backpulses. However, the shear force exerted by cross-flushing is not as effective as backpulsing in removing foulants, especially with the presence of internal fouling within the membrane. The cross-flushing by periodically stopping the permeate flow has proved to be a useful technique to aid to reducing reversible, nonadhesive fouling (248). Microfiltration of yeast cell suspension showed that more time spent on cross-flushing resulted in a slower flux decline.

Sonification involves the use of high-energy, ultrasonic pulses to bombard and dislodge materials from surfaces. The baths commonly are employed to clean lab glassware with the principal function of scouring dirt and particles from surfaces of vessels. The technique has been used in research work to promote aquatic reactions and for dislodging bacterial biofilm for the purpose of analysis (249, 250). The procedure involves sonificating the membrane module in a sonification bath at a frequency of 42 kHz and temperature of 20°C. Introducing some cleaning chemical into the lumen of the membrane and soaking the module in each of the cleaning agents for about half a day performed the chemical cleaning. The membrane modules were cleaned prior to subsequent experiments to remove fouling not removed by the cleaning methods used. The experiments showed that the extent of irreversible fouling was minimized to $<5\%$ of the flux reduction. Permeation flux also increased significantly after sonification, which also confirms that it is an effective method for reducing fouling.

Figure 9 illustrates the extent of cleaning by the various methods (16). Hollow fiber membrane microfiltration units were employed to treat two types of activated sludge wastewater of different particle variations. The performance efficiency of a combination of clean water backwashing, sonification, and chemical cleaning was investigated while evaluating the sonification technique employed. In the study, the underlying cleaning mechanisms and the effectiveness of the cleaning methods to the different types of fouling were treated. The overall results showed that the types of fouling in microfiltration of activated sludge wastewater were down to the initial pore blocking, subsequently followed by cake formation. On the other hand, it was not effective in flux recovery for fouling by pore blocking and therefore the rate of flux recovery decreased per cleaning cycle.

The introduction of flow instability by low-frequency axial pressure and velocity pulsing was investigated and the results conclude that a procedure of intermittent filtration separated by short phases of low pressure and high velocity could sustain a self-cleaning regime (162). The relationships between membrane fouling and cleaning were studied, taking into account flow conditions, transmembrane pressure, pH, membrane properties, and cleaning agents (237). A stirred batch cell and aqueous albumin solution were used to illustrate the relationships and it was observed that fouling was less at the pH extremes than at the isoelectric point for retentive and partially permeable membranes. The partially permeable membranes proved a greater tendency for fouling and were less submissive to cleaning. It was also concluded that as transmembrane pressures increase, fouling occurs and permeate flux is indirectly proportional to the pressure. The operation of a membrane module should follow a "slow startup" in which the operating transmembrane pressure is reached after a while and this suboptimal condition will initially reduce long-term fouling [263].

Another study (207) focused on gas bubbling membrane cleaning during MF, using a flat sheet membrane module. Here, flux was applied intermittently and air bubbles were introduced in the zero flux periods. This operation yielded a 20% rise in productivity. The gas blow back technique is a very effective cleaning technique developed by Vivendi-Memcor for hollow fiber microfiltration (251, 252). High-pressure air is constantly applied to the

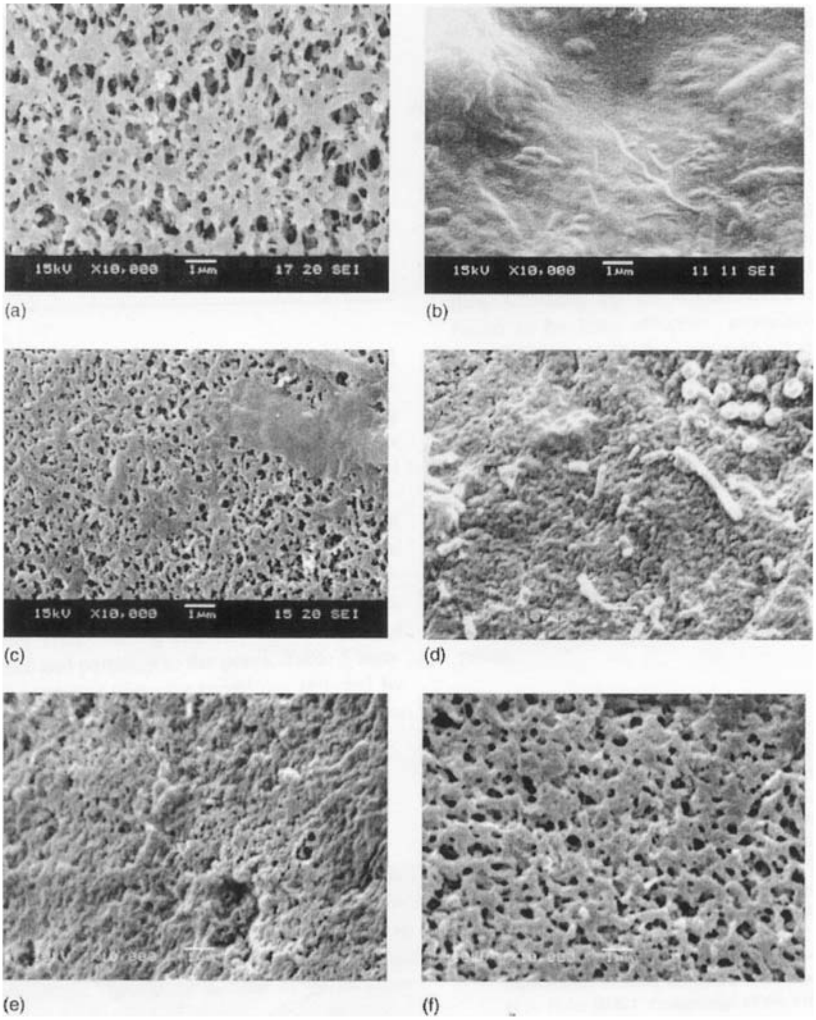

Figure 9. SEM images showing the surfaces of clean membrane, fouled membrane, and used membrane after been cleaned by sonification, chemical cleaning, DI water backwashing, respectively, or by the combination method. (a) new membrane surface, (b) fouled membrane, (c) membrane cleaned by sonification, (d) membrane cleaned by chemicals, (e) membrane cleaned by water backwashing, (f) membrane cleaned by combined cleaning (16).

permeate side and it flows powerfully through the pores, removing fouling deposits and causing pronounced bubbling on the shell side of the module. The frequency is determined by the TMP and is a function of imposed flux and solids content. However, the limitations to this method include its high operating cost via energy usage and its initial capital cost (251–253).

The investigation into the possibility of finding periodic flow regimes consisting of alternate phases of filtration and membrane cleaning leading to large steady-state permeate fluxes was reported (162). This was also related to the situation that presents itself when the flux decline is mostly due to the deposited cake layer on the membrane surface. This particular technique was carried out using $CaCO_3$ suspensions at 30°C, using tubular ceramic membranes. The work confirmed that in the case of superficial membrane fouling of the membrane caused by particles larger than pores of the membrane, a procedure of intermittent filtration separated by short phases of low pressure and high velocity could sustain a self-cleaning regime.

Although wastewater from banknote printing works usually contains large quantities of sodium hydroxide ($\sim$10 g/l), surfactants ($\sim$5 g/l), the treatment of this wastewater involves very high capital and running costs and a very large amount of acid (254, 255). As a result there are still no perfect treatment results. With respect to the UF of wastewater from banknote printing works, the surfactants have the desired effect of membrane cleaning but membrane flux decreases with time due to bad treatment, inadequate cleaning, and the prolongation of time.

A particular study highlighted and investigated the fouling elements of wastewater and the characterization of the membrane used in the ultrafiltration of wastewater from banknote printing works. The aim of the experiments were to simulate the fouling process using model substances, which are found in wastewater from the operations including Turkey red oil, sodium hydroxide, and calcium ions. Turkey red oil was investigated as the sole foulant, and the effects of the calcium ion on the fouling process were also looked into. The other objective was to carry out a cleaning method and determine its effectiveness at controlling and reducing fouling that occurred on the hollow fiber blend membranes (PS/PDC; a molecular weight cutoff [MWCO] = 30,000). Membrane fouling occurred more seriously after the introduction of calcium ion and this is because a dense gel was deposited on the membrane surface. Further experiments showed that a four-step cleaning process could effectively clean the membrane fouled by banknote printing wastewater, but the much better effect can be reached after three cleaning periods. The experimental results of the flow rates, SEM and EDX, TOC, and ICP validated the scale and importance of the value of calcium ion contribution to the fouling process. The cleaning procedure involved cleaning the membrane with deionized water, 0.1 M HCl aqueous solution, deionized water cleaning for a second time and finally with a 1 wt.% NaOH aqueous solution. It proved to be very effective for recovering the optimal membrane performance both at small (laboratory) and large (Plant) scale applications. The reduction of membrane flux appeared to be severe in the second step due to the formation of a denser gel layer on the membrane surface and increased flux was achieved in the fourth step of cleaning. It has been utilized in several printing companies in China with good economic benefits and a substantial reduction in environmental pollution (14).

In order to enhance the membrane performance, the foulants and the fouling mechanisms have to be correctly identified (256). Membrane fouling characteristics and cleaning strategies in a coagulation-microfiltration combination process were investigated for the purification of micropolluted raw water. The modeling methods, SEM and EDS, revealed that fouling on the membrane surface was an integrated action of microorganisms, organic and inorganic matter, while the inner surface was due to biofouling. Results showed that alkaline cleaning effectively removed most of the microorganisms and organic foulants formed on both the surface and inner pores of the membrane. Acidic cleaning was more suited to removing inorganic scales. Calcium was also discovered as the major inorganic element in the foulants (257).

A detailed investigation on a polysulfone membrane that had been fouled by precipitation of milk components was carried out, outlining the effects of different cleaning agents to enhance the recovery of the fouled membrane and improve the performance of the membrane (232). A polysulfone membrane with MWCO of 30 kD was used in all experiments. Some of the chemicals used as cleaning agents included sodium hydroxide, sodium hypochlorite, hydrochloric acid, sulfuric acid, EDTA, and SDS. The results showed that a washing time of 20 min with water before chemical cleaning was very effective. The flux recovery also increased within half an hour using a 0.5 M sodium hydroxide solution but there was no visible enhancement on flux recovery after half an hour. The authors also reported that sodium hypochlorite was capable of particle removal from the membrane surface and the pores due to its strong oxidizing potential. It also causes the membrane to be more hydrophilic, thus increasing the permeate flux. The results from the experiments also concluded that NaOH in the concentration range 0.6–0.8 wt.% causes the best result for chemical washing of polysulfone membranes, but higher concentrations result in flux recovery decrease. Also, sodium hypochlorite showed favorable results at concentrations of 0.2 wt.% but was damaging to the membranes at higher concentrations. The combination of SDS and NaOH can also be used to reach the optimum recovery of the polysulfone membranes used in milk concentration industries.

There are certain problems and practical issues associated with bubble-induced cleaning and its use in reducing fouling and improving flux (214). The problems of foaming and bubble damage to the proteins are considered. It has a high-energy demand, and the use of intermittent or cyclic bubbling is the focus of future efforts to minimize this problem. Optimal bubble size and frequency are parameters that need to be investigated, which would relate to research into bubble-membrane interaction, methods of bubble delivery and introduction, and the benefits. Work was carried out to identify suitable approaches to slow down membrane fouling rates in membrane operations utilizing two methods of offsite chemical and mechanical cleaning and air scouring (258). The method involving chemical cleaning produced a longer operation than compared to mechanical cleaning. Air scouring, on the other hand, prolonged the membrane operation for up to 8 months without need for any form of cleaning.

CONCLUSION

Membrane fouling determines effectiveness and economical feasibility of large-scale operation of pressure-driven membrane processes. This review demonstrates that tremendous efforts have been undertaken to cope with this complex phenomena. It expands the point that alleviation of adverse effect of membrane fouling demands the development of complex approaches. Therefore there is a need for in-depth knowledge of fouling phenomena. Fouling-mitigating measures can involve any aspect of membrane system design, namely the membrane itself, membrane element, alteration and conditioning of treated feed, operating parameters. Membrane cleaning was also discussed since it not only intends to manage with consequences of membrane fouling but also predetermines membrane ability to withstand fouling in multiple cycles of membrane exploitation/cleaning.

Novel development of fouling-resistant membranes continually improves stability of permeate flux in many applications. Alterations of colloid properties of the treated streams provide the most straightforward and historically earliest means to decrease membrane fouling. However, the new insights into fouling phenomena offer new opportunities in the application of this approach. The most fruitful and versatile methodology to mitigate membrane fouling is considered to be optimization of hydrodynamic conditions which include turbulence elevation, alteration of the flow direction (backpulsing/backflushing/backwashing), introduction of gaseous phase (gas sparging, bubbling), and harnessing of additional force fields.

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