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SEMIPERMEABLE MEMBRANES FOR MEMBRANE TECHNOLOGIES

Abstract. The review shows membrane technologies based on the principle of baromembrane processes (microfiltration, ultrafiltration, nanofiltration, reverse osmosis are considered and are increasingly used in industrial use and household purposes). Their main feature is the presence of a semipermeable membrane based on ceramics, polymers or nanocarbon materials with selective permeability for certain components of the separated mixture (charged metal cations, molecules of organic substances, bacteria, viruses).

Keywords: membrane technology, microfiltration, ultrafiltration, nanofiltration, reverse osmosis.

Ion exchange membranes play a leading part in an electrodialyzer, and the performance of an electrodialyzer strongly depend on the characteristics of ion exchange membranes. In order to operate an electrodialyzer effectively, it is necessary to understand the membrane characteristics definitely [1].

The separation of substances by membranes is essential in industry and human life. Of the various separation membranes, the ion exchange membrane is one of the most advanced and is widely used in various industrial fields: electrodialysis, diffusion dialysis, separator and solid polymer electrolyte in electrolysis, separator and solid polymer electrolyte of various batteries, sensing materials, medical use, a part of analytical chemistry, etc. The ion exchange membrane originated from two different sources: the finding of ion exchange phenomena in soil and in explaining biological phenomena in cell membranes. The ion exchange phenomenon was found by the English agriculturist, H.P. Thompson and the chemist J.T. Way in 1850, who noted the adsorption of ammonium sulfate on soil as follows,

$$\mathrm{Ca\text{-}Soil} + (NH_4)_2SO_4 = 2NH_4\mathrm{\text{-}Soil} + CaS0_4$$

Their finding led to the synthesis of inorganic ion exchangers (aluminosilicate corn pounds). Subsequently, the English chemists, B.A. Adams and E.L. Holmes synthesized organic cation and anion exchange resins by the condensation reaction of phenolic compounds having ionic groups and formaldehyde. D’Alelio developed polymerization type ion exchange resins and laid the basis of today's ion exchange resins [2].

Membrane systems excel because they are precisely tailored to the specific requirements of the finished product. To date, we have developed four primary membrane technologies spanning a range of pore sizes that suit numerous applications, from removing salt to filtering large particulates in viscous fluids. Reverse osmosis offers the finest degree of separation, followed by nanofiltration, ultrafiltration, and microfiltration, which has the largest pore size. Membrane technologies can also be used in combination, such as ultrafiltration followed by reverse osmosis for seawater desalination processes. Food, beverage, and general industrial processes utilize membrane pore size and charge to selectively reject macromolecules and ionic species [3].

Figure 1 shows membrane technologies that operate on the principle of baromembrane processes: microfiltration (MF), ultrafiltration (UF), nanofiltration (NF) and reverse osmosis (RS).

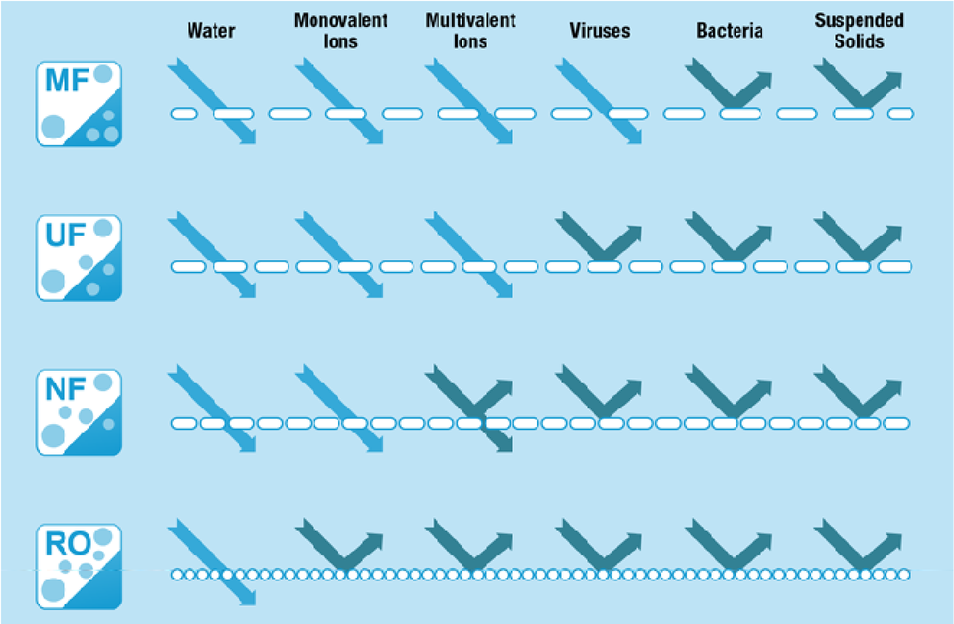

Figure 1 – Comparison of Membrane Technologies

Microfiltration membranes. MF has significant applications in simple dead-end filtration for water, sterile fruit juices and wine, and aseptic pharmaceuticals. However, not all applications that benefit from MF operate successfully in the dead-end mode, and a large portion of the MF market has been captured by crossflow.

The most common of these is the clarification of whole cell broths and purification processes in which macromolecules must be separated from other large molecules, proteins, or cell debris. Clarification of dextrose and highly-colored fruit juices employ MF extremely well. There are also large markets for MF crossflow filtration in wine production, milk and whey de-fatting, and brewing. As with ultrafiltration, MF systems operate at relatively low pressures and come in a variety of configurations [3].

MF membranes with pore sizes of 0.1–10 μm are used extensively for removing contaminants from mixed feed solutions and can isolate a targeted product from such solutions [3, 4]. Commercial MF membranes made from various thermoplastic polymers such as polysulfone, polyethersulfone, poly(vinylidene difluoride) (PVDF), and polyacrylonitrile are used extensively for aqueous feed streams. However, because of membrane solubility in organic solvents, their application for solvent-phase separation is somewhat limited. Postcrosslinking these membranes with suitable chemical agents might prevent the membranes from dissolving in organic solvents [5]. Another concern is that the postcrosslinked membranes can become highly swollen in solvents, and this can result in them losing their separation function and performance. Therefore, organic solvent–resistant MF membranes are desired for specific applications such as solvent-phase filtration, oil–water separation, and porous support of composite membranes [6]; however, recent studies have focused on organic solvent nanofiltration.

For harsh separation conditions such as high polar solvents and high temperatures, filtration membranes made of polytetrafluoroethylene (PTFE) and polyimide (PI) fabric woven are commercially available. Because of their mechanical strength and thermal stability, organosoluble PIs may be the most studied polymers for organic solvent nanofiltration [7]. Organosoluble PI–based membranes are generally prepared through phase inversion processes. However, these membranes remain unsuitable for filtration with feed solution of high polar aprotic solvents. In one study, PI-based membranes were postcrosslinked to enhance their stability in filtration operations. By contrast, conventional aromatic PI-based dense films, which are insoluble in organic solvents, are obtained by casting a poly(amic acid) (PAAc) solution into PAAc films and subsequently converting the films into corresponding PI films through thermal imidization. However, fabricating PI-based porous membranes through a nonsolvent phase separation process is impossible with a PAAc precursor because of the strong interaction between PAAc and water (the nonsolvent). To address this problem, Kang et al. [3, 8] attempted to reduce the interaction between PAAc and water through partial imidization of the PAAc precursor, and successfully prepared asymmetric PI membranes. In another such attempt, Chun et al. [8] added PAAc solvent (N,N-dimethylacetamide [DMAc]) into a coagulation solution to delay the demixing phase inversion. As not many successive works have been reported on preparation of solvent-resistant PI-based porous membranes, porous membranes made of thermosetting resins have been reported [9]. However, applying these membranes to filtration is rare because of the inconvenience of fabrication and unsatisfactory membrane properties.

As an alternative to postcrosslinking thermoplastic polymer–based membranes during fabrication processes, crosslinked membranes made of organosoluble self-crosslinkable polymers are relatively attractive because they can be fabricated through the conventional process. In the present study, a linear polybenzoxazine (PBz; figure 2) [10] was utilized because of its self-crosslinking ability, low cost, and processing property. Moreover, crosslinked PBz exhibits some attractive properties for membrane separation, including low-surface free energy [11], excellent solvent resistance, and high thermal stability. Crosslinked PBz–based dense membranes for pervaporation and electrospun nanofiber mats for oil–water separation and separators for lithium-ion batteries have been reported. In the present study, porous membranes of linear PBz were obtained through a conventional vapor-induced phase separation (VIPS) process and subsequently in situ thermally crosslinked through a simple thermal process (Fig. 2). Additionally, applications of the crosslinked PBz–based membranes for size-selective particle separation in organic solvents and for separating surfactant-stabilized oil–water emulsion were examined [12].

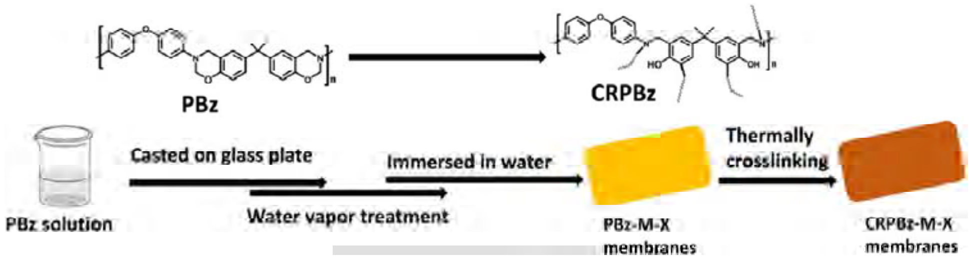

Figure 2 – Fabrication of cross-linked PBz based membranes

Ultrafiltration membranes. UF is a pressure-driven process that removes emulsified oils, metal hydroxides, colloids, emulsions, dispersed material, suspended solids, and other large molecular weight materials from water and other solutions. UF membranes are characterized by their molecular weight cut-off.

UF excels at the clarification of solutions containing suspended solids, bacteria, and high concentrations of macromolecules, including oil and water, fruit juice, milk and whey, electrocoat paints, pharmaceuticals, poly-vinyl alcohol and indigo, potable water, and tertiary wastewater [13].

In recent decades, UF has been extensively used in drinking water treatment. Compared to conventional treatment, UF provides treated water with better quality. Complete removal of pathogens and particulate impurities can be achieved with an UF membrane, which significantly improves the biological security of drinking water. However, although the UF process is recognized as an advanced technology for producing high-quality drinking water, membrane fouling, which leads to reduced membrane productivity and increased energy consumption, remains as an obstacle in the long-term operation of UF, particularly in full-scale waterworks [14].

Natural organic matter (NOM) in surface water, mainly composed of humic acids (HA), polysaccharides, proteins and lipids, has been identified as the most problematic membrane foulant and causes severe membrane fouling, particularly irreversible fouling. Therefore, a variety of pretreatments are adopted prior to membrane filtration to retard membrane fouling. Organic foulants can be removed or transformed to a certain extent with pretreatment, and UF membrane fouling is alleviated to some degree. Widely investigated pretreatments include coagulation, adsorption, bio-filtration and peroxidation. Coagulation is generally considered one of the most successful pretreatments for fouling control, because it can effectively remove the high molecular weight (MW) fraction in NOM, which is primarily responsible for irreversible membrane fouling. However, coagulation is ineffective in the removal of low-MW and hydrophilic fractions in NOM, which may also contribute to membrane pore blocking [15].

Adsorption pretreatment with powdered activated carbon (PAC) or ion exchange resins can eliminate low-MW organics and improve feed water quality, but the high demand for adsorbents 66 may offset the limited benefits associated with fouling mitigation obtained by adsorption. Moreover, the presence of absorbents sometimes aggravates rather than mitigates membrane fouling. For example, investigated a hybrid PAC-UF process for surface water treatment and found that PAC and HA formed a combined fouling layer on the membrane surface, resulting in a significant synergistic fouling effect [16]. In general, both coagulation and adsorption pretreatment only succeed in transferring NOM fractions from feed water to the solid phase, and further treatment/disposal of the solid waste is still required. Although coagulation remains the most popular method for minimizing membrane fouling, pre-oxidation attracts greater interests in recent years due to its capacity in removing NOM, particularly in the occurrence of emerging organic contaminants. Among the investigated oxidation methods, ozonation has been most intensively investigated. However, residual ozone in feed water may be detrimental to the membrane material, resulting in accelerated membrane aging [17].

In recent years, an advanced oxidation process (AOP) using activated peroxymonosulfate (PMS) or persulfate (PS) has attracted much attention for the degradation of micro pollutants such as pharmaceutical organic compounds, algal toxins and odor compounds [18, 19]. Sulfate radicals (SO_4^{-}), produced via activating PMS or PS with UV and reducing ions, have very high oxidation capacity (E_0=2.65-3.1 V) and can degrade both NOM and micro pollutants [20]. Hence, it is reasonable to assume that oxidation pretreatment with activated PMS or PS would contribute to NOM fouling control during surface water treatment using low-pressure membrane filtration. To our knowledge, there are only two reports involving the control of membrane fouling by model foulants and NOM with PMS pre-oxidation activated by ferrous ions (Fe (II)). Fe (II)/PMS pretreatment (15μM) was demonstrated to effectively alleviate fouling caused by humic acids and alginate, but fouling caused by bovine serum albumin was aggravated except when applied at an increased PMS dose (50 μM) was applied [21]. For surface water, NOM was effectively removed via dual mechanisms, i.e., pre-oxidation with sulfate radicals and coagulation with in situ formed Fe (III), resulting in substantial reductions in organic compounds, particularly for macromolecular fractions, and thus increased membrane permeability and fouling reversibility [13, 21]. Despite great performance in fouling control, the Fe (II)/PMS pretreatment may increase sludge due to precipitation of ferric flocs, particularly for practical applications. To address this issue, an ultraviolet-activated persulfate (UV/PS) process is alternatively put forward for UF membrane fouling control in this work. UV irradiation, which is widely applied in disinfection for both drinking water and wastewater effluent, is a relatively cleaner activation method for the generation of sulfate radicals compared to Fe (II). In addition, the UV/PS process proves to be effective in degrading a variety of emerging organic compounds such as sulfamethoxazole, methyl paraben, haloacetonitriles. In terms of fouling control performance and the mechanisms involved, the UV/PS pretreatment has not yet been systematically investigated [22].

The objective of study [13] was to evaluate the performance of a combined process of UV/PS and UF for surface water treatment. To gain insight into the effects of UV/PS pretreatment on membrane fouling, the amounts and characteristics of NOM before and after pretreatment were systematically compared using fluorescence spectra, MW distribution and hydrophobicity/hydrophilicity. Moreover, filtration tests were performed using a continuous-flow immersed UF system, which could better simulate practical applications. The fouled membranes were further analyzed with scanning electron microscopy (SEM) and attenuated total reflection-Fourier transform infrared spectroscopy (FTIR) to gain more insight into mechanisms for NOM fouling control via UV/PS pretreatment.

In this study, the effects of UV/PS oxidation on UF membrane fouling by NOM in surface water were investigated. The following conclusions can be drawn:

1. NOM in surface water was substantially degraded by UV/PS pretreatment with UV254 and DOC decreases of 97% and 58%, respectively, within 120 min at a PS dose of 0.6 mM. UV-adsorbing fractions in NOM were preferentially degraded.

2. A four-component model described the fluorescent EEM spectra of NOM well and the dominance of C3 over other components was verified in terms of fluorescent intensity. UV/PS pretreatment was most effective in removing tryptophan-like proteins, followed by microbially derived humic-like substances.

3. UV/PS pretreatment significantly retarded irreversible UF membrane fouling (~75%) caused by NOM. The performance of fouling control considerably improved at increased PS doses and extended UV irradiation times.

4. Mechanisms for NOM fouling control using UV/PS pretreatment include the preferential removal of hydrophobic fractions and degradation of medium-MW and high-MW compounds into hydrophilic small molecules, which were significantly smaller than the membrane pores.

A combined UV/PS system, in which PS was activated by UV irradiation to generate reactive radicals such as $SO_4\cdot^-$ and $HO\cdot$ via Eq. (1) – Eq. (3), was employed to pretreat the river water [22, 23]. Figure 3 (a) shows a schematic diagram of the oxidation reactor. The oxidation reactor consisted of a cylindrical reactor coated with silver paper, a low pressure mercury UV lamp with a quartz tube pro-viding principal light emission at 254 nm, a peristaltic pump to maintain solution circulation, and a thermostatic water-bath to stabilize water temperature at 20 ± 1 °C. The height and inner diameter of the reactor were 28 and 9 cm, respectively. The UV lamp, which was placed in the centerline of the cylindrical reactor axially along the length of the reactor, was immersed into feed water to

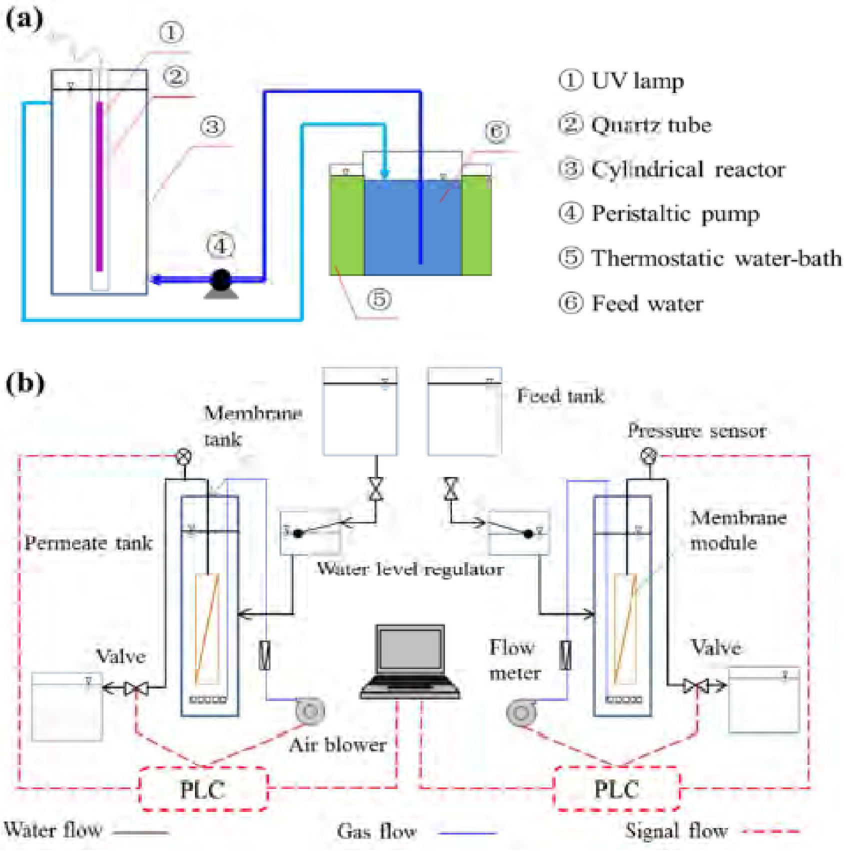

Figure 3 – Schematic diagrams of the oxidation reactor and immersed UF system

enhance penetration of UV light. The incident light intensity of the UV lamp was determined 0.44 μE L^{-1} s^{-1} as by iodide-iodate chemical actinometry. The average fluency rate was estimated to be 1.54 $mWcm^{-2}$ using an integrated form of the Beer-Lambert law. The lamps were warmed up for 15 min prior to reaction to ensure a stable output. In this work, PS was applied at the doses of 0, 0.05, 0.1, 0.2, 0.4, and 0.6 mM. The UV irradiation time was investigated within a range of 0–120 min, corresponding to a UV fluency range of 0-1.1×105 mJ cm^{-2}. To quench the residual oxidants, $Na_2S_2O_3$ were added into samples immediately after sampling at the stoichiometric doses of PS applied. The terminator dose was equivalent to the concentration of added PS according to the stoichiometric criteria.

$$S_2O_8{}^{2-} \xrightarrow{UV} 2SO_4^{\cdot-} \quad \emptyset = 1.4 \tag{1}$$

$$SO_4^{\cdot-} + \mathrm{OH}^- \rightarrow \mathrm{SO}_4^{2-} + \mathrm{HO}^{\cdot} \quad k = 6.5 \times 10^7\ M^{-1}s^{-1} \tag{2}$$

$$SO_4^{\cdot-} + H_2O \rightarrow \mathrm{HSO}_4^{2-} + \mathrm{HO}^{\cdot} \quad k = 8.3\ M^{-1}s^{-1} \tag{3}$$

An immersed UF experimental system was described in detail in our previous work. The system was comprised of a membrane tank, a high-level tank, a peristaltic pump, a pressure transducer, a programmable logic controller and a personal computer (figure 1 (b)). Tiny membrane modules with an effective membrane area of 21.7 cm^2 were fabricated in the lab. Before use, the membrane module was thoroughly cleaned with deionized water to remove organic residue on the membrane surface. The multi-cycle UF experiments were performed under a constant permeate flux 35 Lm^{-2} h^{-1}. Each UF cycle consisted of min filtration and 1 min backwashing at 70 Lm^{-2} h^{-1} with the permeate water. The trans-membrane pressure (TMP) was automatically logged by an online pressure transducer. Fouling resistances were calculated by equation. The raw water and pretreated water were stored in feed tanks and continuously fed into the UF systems. Filtration tests were performed in triplicate.

Nanofiltration membranes. NF functions similarly to reverse osmosis, but is generally targeted to remove only divalent and larger ions. Monovalent ions such as sodium and chloride will pass through a nanofiltration membrane, therefore many of its uses involve de-salting of the process stream (figure 4).

In the production of lactose from cheese whey, for example, NF concentrates lactose molecules while passing salts, a procedure that purifies and concentrates the lactose stream. In water treatment, NF membranes are used for hardness removal (in place of water softeners), pesticide elimination, and color reduction. It can also be used to reclaim spent NaOH solutions, in which case the permeate stream is purified NaOH, allowing reuse many times over.

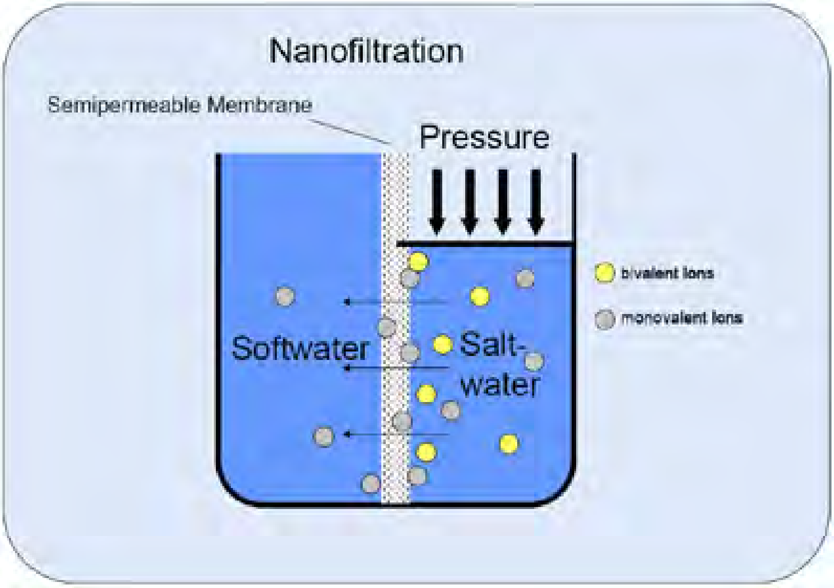

Figure 4 – NF system

High water permeability and rejection of solutes are features which make NF membranes economically viable in water softening applications, attractive for water purification and removal of harmful organic solutes from water [24]. However, theirs in general hydrophobic selective layer facilitates adsorption and the transport of organic solutes [25], which often results with inadequate removal of, for example pesticides, pharmaceuticals and endocrine disrupting compounds, and limits their practical use [26]. Rejections of non-hydrophobic or ionized organics are generally higher than those of non-ionized hydrophobic solutes due to much lesser solute affinity toward membrane, or charge repulsion through NF membranes. The latter was confirmed in a recent study of authors [27] on the RO (SWC1) membrane, where it was shown that non-ionized phenolic solutes enter the selective layer, and freely partition inside by an order of ten, even if solute radius is close to the radius of the pore. Moreover, it was shown that sorption of organics in the selective layer is unfavourable because it changes membrane characteristics in terms of both salts and water permeability.

Authors [28] correlated membrane surface hydrophilicity with membrane fouling and it can be assumed that rejection of at least some of organics could be improved by rendering the membrane surface more hydrophilic. Furthermore, authors [29] found that RO membranes, declared as low fouling, are resistant to fouling in terms of specific flux decrease over time. It is widely accepted today that commercial brackish water RO membranes declared as low fouling, such as BW30 and LFC, have increased oxygen content and are probably coated [30]. Our past study also found [31] that LFC membrane was more resistant to fouling in terms of irreversible pesticide adsorption and flux decrease compared to other membranes.

Many studies focused on surface modification of membranes [32, 33] while the general benefits of modifications are permanently reduced membrane fouling [34] and increased rejection of proteins or organic solutes and salts. But, according to authors' knowledge very few were focused on a mechanism which could explain why membranes became better rejecting to some organic solutes while rejections of some solutes remain the same or even decrease. This study aimed at proposing a plausible way to study such mechanism. Commercial thin film NF membrane, NF270, was coated with a thick layer of polyvinyl alcohol (PVA) and the rejections of various organic solutes of different sizes and physicochemical properties were studied before and after the addition of PVA layer. Pesticides, bentazone and tebuconazole, were used in this study as model compounds which represent an entire class of high affinity, non-ionized and hydrophobic compounds such as bisphenol A and hormones.

NF performance as a function of feed temperature is relevant to several industrial settings including pretreatment for scale control in thermal desalination. Understanding of solute transport as a function of temperature is critical for effective membrane and system design. In wotk study, nanofiltration is modeled at 22, 40 and 50 °C using the Donnan Steric Pore Model with dielectric exclusion (DSPM-DE). This modeling includes the temperature dependence of the three modes of solute transport, namely the convective, electromigrative, and diffusive modes, and the three mechanisms of solute exclusion, namely Donnan, steric, and dielectric exclusion. The effect of temperature is captured through the variation of membrane parameters and solvent and ionic mobilities with temperature. Authors compare the most abundant ionic compound in natural water, sodium-chloride with magnesium-chloride to portray how the salt passage and rejection change for a 1:1 salt compared to a 2:1 salt, and analyze Arabian Gulf seawater to understand how rejection of scale-forming ions, such as Mg^{2+} and Ca^{2+}, is affected by feed temperature. In all cases, solute transport increases with temperature, attributed predominantly to the cumulative effect of membrane parameters and only to a small extent (up to 5%) to the solvent viscosity and ion diffusivity together [35].

In work [36], polysulfone (PSf) substrates with different properties were made by varying the polymer concentration in the dope solution in the range 12–20 wt.%. Polyamide (PA) thin layers were then formed via interfacial polymerization between piperazine and trimethylchloride over the PSf substrates. Both top PA thin layers and bottom PSf substrates were characterized with respect to physicochemical properties, structural morphology, and water flux/salt rejection to investigate the influence of substrate properties on the characteristics of PA thin layers. Physical properties of the PA layers were reported to be altered using different PSf substrate properties and were in good agreement with the change in water flux. From the FESEM pictures, it is found that the thickness of PA layer increased as the surface pore size of support membrane decreased. The change in the membrane structural properties in particular pore size is found to portray significant contribution to the changes of formed PA layer. Interestingly, only slight changes on Na_2SO_4 and $MgSO_4$ salt rejection were reported on any TFC membranes. Considering both water permeability and salt rejection rate, the best performing TFC membrane produced in this work was the membrane made over substrate of 15 wt.% PSf concentration.

Reverse osmosis membranes. RO membranes feature the smallest pores and involve, appropriately enough, the reversal of osmotic pressure in order to drive water away from dissolved molecules. Strictly speaking, RO is not a size exclusion process based on pore size; it depends on ionic diffusion to affect separation. One of its common applications is seawater desalination, in which pure water is produced from a highly saline feed stream, similar to evaporation with far better economy (figure 5).

RO is also used in cheese whey concentration, fruit juice concentration, ice making, car wash reclamation, wastewater volume reduction, and other industrial processes, with the goal of producing a pure filtrate (typically water) or retaining the components. Because the osmotic pressure of many process streams is quite high, RO membranes must operate at pressures of 400-1,200 psi (29-83 bars), which restricts available membrane geometries.

Desalination, especially the RO membrane technology, has been recognized as an effective purification technology to supply potable water from seawater and wastewater. Compared with the thermal technology desalination, the RO techno-

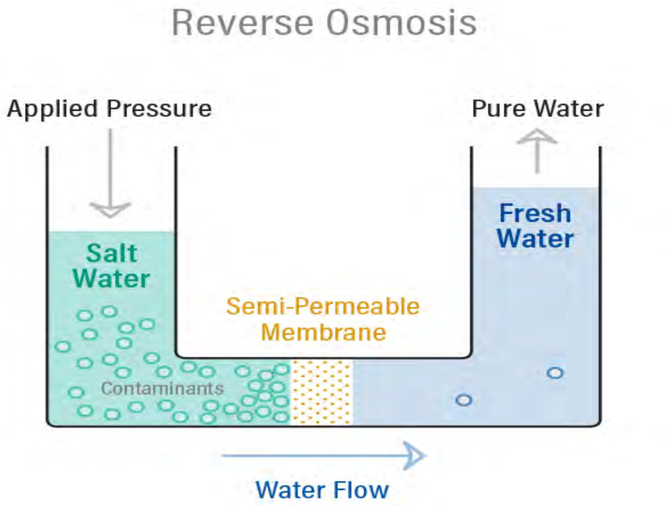

Figure 5 – Schematic diagram of a typical RO system

logy requires less energy input. However, the RO technology is still a high-energy consumption industry. High-pressure pumps are applied to feed the seawater through the RO membrane module at a high pressure, ranging from 6 to 8 MPa. This causes a large amount of consumption in electricity cost, 40% in the overall operating cost [37]. Thus, the energy recovery device (ERD) has been proposed to recover the high-pressure energy from the brine reject stream and deliver the high-pressure energy back to the seawater stream. These devices can significantly decrease the electricity consumption and improve the RO system efficiency. Based on their working principle, ERDs can be categorized as the turbine-type device and the isobaric device [38, 39]. Due to applying positive displacement principle [40], the isobaric ERD can achieve higher energy recovery efficiency than the turbine-type ERD [41–43]. The rotary-type ERD (RERD) and the piston-type ERD are two types of isobaric ERDs nowadays [44, 45]. Figure 6 shows a typical RO system equipped with a RERD [46].

During the energy recovery process of the ERED, the seawater stream is pressurized directly by the brine reject stream in a rotor duct [40]. Because there is no physical piston between the seawater stream and the brine reject stream in the rotor duct, the RERD can achieve a highest energy recovery efficiency. The PX Pressure Exchanger device is one of the typical commercial product of the RERD, which can achieve an energy recovery efficiency of up to 98% [47]. However, for lack of the physical piston, the seawater stream will directly contact with the brine reject stream, resulting in a formation of a mixing zone between the two streams. The mixing zone increases the salinity of the seawater stream which would be supplied into the RO membrane module, leading to higher electricity consumption of high-pressure pumps in the RO system [46]. Therefore, much research has been carried out on the effect of flow dynamics on the mixing

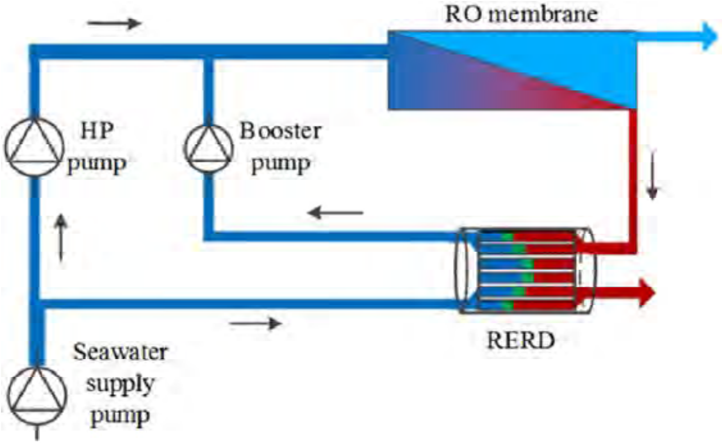

Figure 6 – Schematic of RO system with RERD

process. Mei et al. [48] performed a theoretical research on the efficiency of a RERD. They found that the longitudinal diffusivity affected the mixing rate in the duct under the laminar flow condition. Cao et al. [49] numerically explored the mixing performance and the flow pattern. They pointed out that the mixing rate could be controlled at a low value when the flow pattern in the duct was closed to a plug flow. In work [50] authors performed a 2D simulation to investigate the flow characteristic in the duct. The simulation results showed that the rotor speed and the working condition could affect the formation and movement of the mixing zone. They suggested that the characteristic of the mixing zone should regard as a key factor on the performance of a RERD to guarantee the salinity of the seawater stream. Xu et al. [51] researched the mixing process in the duct with a 3D simulation. The flow structure showed a liquid piston formed between the seawater stream and the brine reject stream. The liquid piston prevented these two streams over mixing with each other. From the aforementioned discussion, it is reasonable to conclude that the flow structure and the formation of the mixing zone have a direct influence on the mixing process. However, due to the high-speed rotation of the duct, none of the foregoing literature has investigated the flow structure or the formation of mixing zone with experimental methods, such as the particle image velocimetry (PIV) measurement.

The purpose of the experiment reported here was to research the detailed flow characteristics in the duct. A visualization apparatus of a RERD (hereinafter abbreviated as V-RERD) was proposed to measure flow structures in the duct by a two-dimensional (2-D) PIV measurement. For easy measurements, this visualization apparatus was set with a single stationary duct and two rotary endcovers in this experiment. The experiment results may be beneficial to better understanding flow dynamics and the mixing zone formation during the working process.

In work [52], a visualization apparatus of a RERD with a stationary duct and two rotary endcovers, employing the same working principle as the typical rotary-type ERD, was proposed to visualize the flow structure in the duct. A 2-D PIV measurement was performed to directly measure flow characteristics.

According to experiment results, an "entrance effect" can be observed in the duct, resulted from the relative rotation of the endcover and the duct. It caused the formation of unstable flows with three-dimensional structures at the duct entrance. In addition, it led to a higher turbulence intensity level in the vertical plane than that in the horizontal plane. The liquid piston, a stable flow region with almost uniform velocity magnitude and low turbulence intensity, can be clearly identified in the middle section of the duct, effectively preventing the mass transfer between the seawater stream and the brine stream. From instantaneous flow fields, the vortex evolution was captured at the duct entrance and the duct exit. Due to the repeating sequence of the vortex formation, expansion and motion in the working cycle, the turbulence intensity increased significantly, which may result in an increase in the mixing degree between the two streams and eventually degrade the RERD performance. These experimental results can be used to validate numerical predictions as well as for designing purposes. In the future, more experimental research needs to be carried out to clarify the fundamental mechanism of the pressure recovery and mass transfer.

Ion exchange membranes emerging as renewable materials play prominent roles in promoting the development of traditional industry and innovative energy technologies. To date, most of the attention has been focused on exploring promising materials, developing diverse preparation methods, and expanding a wide variety of applications related to ion exchange membranes. Over the past ten years, such field has significantly bloomed and a large number of achievements have been gained. To date, there are a tremendous number of ionic polymer candidates available for the preparation of various kinds of ion exchange membranes, including cation exchange membranes, anion exchange membranes, monovalent ion perm-selective membranes, mixed matrix membranes, and bipolar membranes. Although progresses in exploring new ion exchange membranes are prominent, there are still a few challenges, which need to be urgently addressed. For example, the chemical stability of the membranes should be promoted furthermore to ensure the longevity of their lifetime in various applications.

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Резюме

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МЕМБРАНАЛЫҚ ТЕХНОЛОГИЯЛАРҒА АРНАЛҒАН ЖАРТЫЛАЙ ӨТКІЗГІШТІ МЕМБРАНАЛАР

Шолу мақаласында баромембраналық үдерістер (микрофильтрация, ультрафильтрация, нанофильтрация, кері осмос) қағидаттарына негізделген және өнеркәсіптік пайдалануда және тұрмыстық мақсаттарда жиі пайдаланылатын мембраналық технологиялар қарастырылған. Полимерлер, керамика немесе нанокөміртекті материалдар негізінде бөлінетін қоспаның белгілі компоненттері бойынша (металдардың зарядталған катиондары, органикалық заттардың молекулалары, бактериялар, вирустар) талғамды өткізгіштігі бар жартылай өткізгіш мембрананың болуы олардың басты ерекшелігі болып табылады.

Түйін сөздер: мембраналық технологиялар, микрофильтрация, ультрафильтрация, нанофильтрация, кері осмос.

Резюме

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ПОЛУПРОНИЦАЕМЫЕ МЕМБРАНЫ ДЛЯ МЕМБРАННЫХ ТЕХНОЛОГИИ

В обзорной статье рассмотрены мембранные технологии, работающие по принципу баромембранных процессов (микрофильтрация, ультрафильтрация, нанофильтрация, обратный осмос) и получающие все большее применение в промышленности и бытовых целях. Главной их особенностью является наличие полупроницаемой мембраны на основе полимеров, керамики или наноуглеродных материалов с селективной проницаемостью по определенным компонентам разделяемой смеси (заряженные катионы металлов, молекулы органических веществ, бактерии, вирусы).

Ключевые слова: мембранные технологии, микрофильтрация, ультрафильтрация, нанофильтрация, обратный осмос.