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Bench scale electrodeionization for high pressure boiler feed water

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HIGHLIGHTS

- ▶ Long term performance of bench scale EDI showed stable and high product quality.
- ▶ Technical and economical aspects were evaluated for high pressure boiler feed water.
- ▶ Dissolved CO₂ in water (HCO₃⁻) is a suspected substance that influences the pH.
- ▶ The specific water cost was US\$0.53/m³, lower than existing ion exchange bed.
- ▶ The main operating costs were membrane replacement and electricity.

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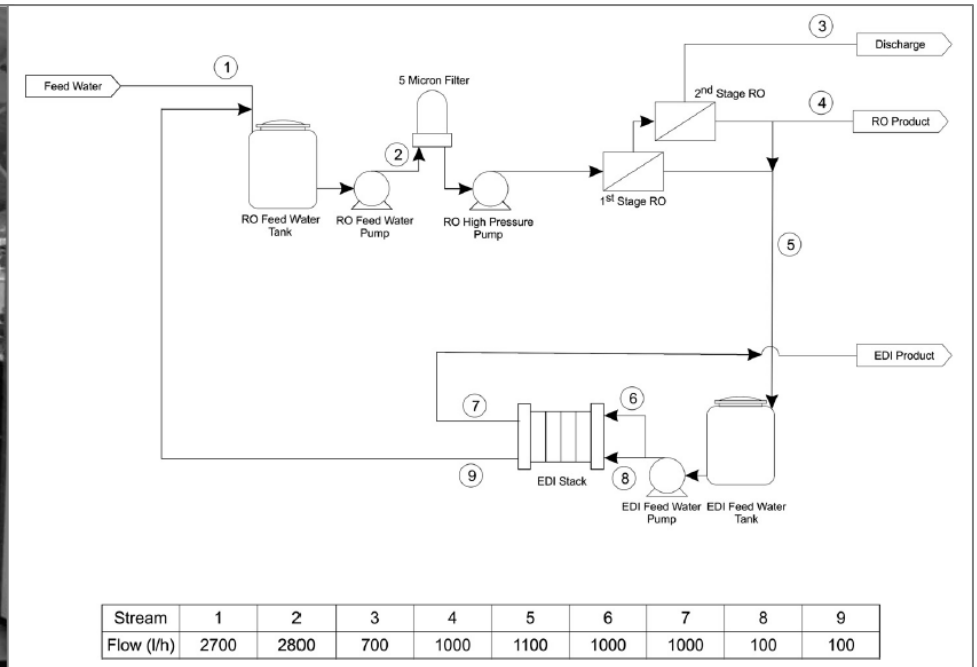
ABSTRACT

In this paper, a bench scale RO/EDI system for high pressure boiler feed water is reported. Technical and economical aspects were evaluated to determine whether RO/EDI system is feasible to replace existing ion exchange bed. The EDI module used in this study was all filled electrodeionization type with mixed bed ion exchange filler. All product quality of demin water produced by RO/EDI during bench scale test shows good water quality (conductivity: 0.3–0.4 µs/cm; pH: around 6.3; silica: 0.00–0.01 ppm; and Na: <0.003 ppm), even better than existing demin water system specification (conductivity: <5 µs/cm; pH: 6.5–8.5; silica: <0.12 ppm; and Na: <0.3 ppm), except pH. Dissolved CO₂ in water (HCO₃⁻) is a suspected substance which is present in RO/EDI product water that influences the pH. The specific water cost of RO/EDI was US\$0.53/m³ lower than existing ion exchange beds, US\$0.66/m³. The main operating costs were membrane replacement and electricity cost. Long term performance of the RO/EDI system showed stable and high product quality even during periods when the feed solution has relatively high conductivity.

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Riset

Bench scale electrodeionization for high pressure boiler feed water



Electrodeionization (EDI)

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Removal of inorganic contaminants in sugar refining process using electrodeionization

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ABSTRACT

This paper reports performance of an electrodeionization (EDI) system during removal of inorganic contaminants in sugar refining process. Dilute compartments of EDI stack were filled with mixed ion-exchange resins (strong acid cation-exchange and strong base type I anion resins). Experiments were then conducted at both batch and continuous operation mode. The results showed that EDI is able to remove inorganic contaminants as well as colour body from sugar solutions. At relatively high sugar concentration, significant decrease in ions removal is observed. The increase of current density and applied voltage had little impact on ions removal and lead to current efficiency and pH reduction. The colour removal may be associated to complex bond (organic–inorganic) breakage due to water dissociation inside the dilute compartment.

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Combined ultrafiltration-electrodeionization technique for production of high purity water

Anita Kusuma Wardani, Ahmad Nurul Hakim, Khoiruddin and I Gede Wenten

ABSTRACT

Electrodeionization (EDI) is the most common method to produce high purity water used for boiler feed water, microelectronic, and pharmaceutical industries. Commonly, EDI is combined with reverse osmosis (RO) to meet the requirement of EDI feed water, with hardness less than 1 ppm. However, RO requires a relatively high operating pressure and ultrafiltration (UF) as pretreatment which results in high energy consumption and high complexity in piping and instrumentation. In this work, UF was used as the sole pretreatment of EDI to produce high purity water. Tap water with conductivity 248 µS/cm was fed to UF-EDI system. The UF-EDI system showed good performance with ion removal more than 99.4% and produced water with low conductivity from 0.2 to 1 µS/cm and total organic compounds less than 0.3 ppm. Generally, product conductivity decreased with the increase of current density of EDI and the decrease of feed velocity and UF pressure. The energy consumption for UF-EDI system in this work was 0.89–2.36 kWh/m³. These results proved that UF-EDI system meets the standards of high purity water for pharmaceutical and boiler feed water with lower investment and energy consumption than RO-EDI system.

Key words | conductivity, electrodeionization, high purity water, ion removal, ultrafiltration

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Pineapple juice acidity removal using electrodeionization (EDI)

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ABSTRACT

The applicability of EDI for organic acid removal in pineapple juice was investigated in this study. Using a bench-scale EDI, the influence of operation parameter, such as current density and feed flow rate, were evaluated against the ion transport flux and current efficiency. It was suggested that more acid removal and higher current efficiency were observed with the increase of feed flow rate and current density. EDI operation modified the physicochemical properties of the decalcified pineapple juice. The pH of the decalcified juice decreased, regardless of the removal of organic acids. Significant depletion of TDG occurred due to sugars' adsorption into the ion exchange resin. In addition to sugars, ion exchange resins might also interact with the color constituent in the pineapple juice and resulted in a color transformation of the decalcified juice. Vitamin C, which is an organic acid, was also dissociated and removed from the pineapple juice.

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Techno-economic comparison of pilot-scale EDI and BWRO for brackish water desalination

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ABSTRACT

In this paper, a pilot-scale electrodeionization (EDI) was designed and operated for brackish water desalination to produce drinking water. Technical and economic feasibility of pilot-scale EDI was investigated and compared to recently installed brackish water reverse osmosis (BWRO) mini-plant with equal production capacity. It was found that EDI could remove more than 98% of salt ions from brackish water at the optimum operating condition (45 V). From an economic point of view, EDI was economically potential as an alternative to the BWRO process which offered a lower capital investment (US\$ 5076) than the existing BWRO plant (US\$ 8447). The specific water production cost of the EDI process was US\$ 0.50/m³ which was comparable to the specific cost of BWRO process, US\$ 0.42/m³. The economic analysis from a long-term perspective shows that EDI is more economical than the BWRO up to around 20 y of operation. These results indicate that EDI is an attractive alternative to BWRO for brackish water desalination.

Keywords: Brackish water; Desalination; Drinking water; Economic; Pilot plant

Electrodeionization (EDI)

Review paper

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CHEMICAL REVIEWS

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Electrochemical Methods for Water Purification, Ion Separations, and Energy Conversion

Mohammad A. Alkhadra, Xiao Su, Matthew E. Suss, Huanhuan Tian, Eric N. Guyes, Amit N. Shocron, Kameron M. Conforti, J. Pedro de Souza, Nayeong Kim, Michele Tedesco, Khoiruddin Khoiruddin, I Gede Wenten, Juan G. Santiago, T. Alan Hatton, and Martin Z. Bazant*

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ABSTRACT: Agricultural development, extensive industrialization, and rapid growth of the global population have inadvertently been accompanied by environmental pollution. Water pollution is exacerbated by the decreasing ability of traditional treatment methods to comply with tightening environmental standards. This review provides a comprehensive description of the principles and applications of electrochemical methods for water purification, ion separations, and energy conversion. Electrochemical methods have attractive features such as compact size, chemical selectivity, broad applicability, and reduced generation of secondary waste. Perhaps the greatest advantage of electrochemical methods, however, is that they remove contaminants directly from the water, while other technologies extract the water from the contaminants, which enables efficient removal of trace pollutants. The review begins with an overview of conventional electrochemical methods, which drive chemical or physical transformations via Faradaic reactions at electrodes, and proceeds to a detailed examination of the two primary mechanisms by which contaminants are separated in nondestructive electrochemical processes, namely electrokinetics and electrosorption. In these sections, special attention is given to emerging methods, such as shock electro dialysis and Faradaic electrosorption. Given the importance of generating clean, renewable energy, which may sometimes be combined with water purification, the review also discusses inverse methods of electrochemical energy conversion based on reverse electrosorption, electro wetting, and electrokinetic phenomena. The review concludes with a discussion of technology comparisons, remaining challenges, and potential innovations for the field such as process intensification and technoeconomic optimization.

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Historical Perspective

Novel ionic separation mechanisms in electrically driven membrane processes

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ABSTRACT

Electromembrane processes including electrodialysis (ED) and related processes are usually limited by diffusion transport of ions from a bulk solution to ion exchange membranes. The diffusion limited current (DLC) occurs when the concentration at membrane surfaces vanishes and approaches zero. Increasing the applied potential difference above this point has no substantial effect on ion transport and causes operational problems such as low current efficiency, high energy consumption, and mineral scaling. However, it is evident from numerous studies that operating at overlimiting current (OLC) is possible and allows one to enhance the mass transfer of an electromembrane process. While OLC is sometimes possible by electrochemical means, such as water splitting or current induced membrane discharge, it has been found that exotic ion transport mechanisms, such as ion concentration polarization in micro/nanofluidic systems, desalination shock waves, and ionic bridges, can provide novel electrokinetic means of achieving OLC. In this paper, these novel ionic separation mechanisms and their role in enhanced current transfer are reviewed in the context of emerging electromembrane processes, such as shock ED and electrodesalination (EDN).

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Heterogeneous Ion-Exchange Membrane

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Effect of hydrophilic additive and PVC polymerization degree on morphology and electrochemical properties of PVC-based heterogeneous cation-exchange membrane

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ABSTRACT: Membrane solution composition is one of the important factors that determine properties of ion-exchange membranes. In this study, a PVC-based heterogeneous cation-exchange membranes were prepared by the solution casting method. Effect of a hydrophilic additive [poly(ethylene glycol), PEG400] and degree of polymerization of poly(vinyl chloride) (PVC) on the morphology and electrochemical properties of the cation-exchange membrane were investigated. The results revealed that the hydrophilic additive can improve membrane properties, including water uptake (WU), ion-exchange capacity (IEC), conductivity, and permselectivity. The improvement might be associated with an increase in accessibility of functional sites in the membrane matrix due to a higher hydrophilicity, indicated by a reduction of water contact angle and the greater void fraction shown by scanning electron microscopy. However, the permselectivity slightly decreased as the additive concentration was increased further. Meanwhile, increasing the degree of polymerization and PVC concentration resulted in higher permselectivity and lower conductivity, which might be due to a better ionic distribution and a lower void fraction. Overall, the prepared membranes had relatively good conductivities (up to ~25 mS/cm) and permselectivities (up to ~0.82). In general, the conductivity increases with increased WU and IEC, while the permselectivity showed the opposite trends. This could be associated with the effect of Donnan exclusion indicated by the IEC/WU ratio and the Donnan equilibrium constant of the cation (K^+). © 2018 Wiley Periodicals, Inc. *J Appl Polym Sci* 134: 46990, 2018

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INTRODUCTION

Recently, membrane technology has rapidly developed and has been applied in a wide range of industrial sectors due to its outstanding features.^{1–4} Easy efficiency, high separation capacity and selectivity, process intensification, and low investment cost are several advantages that make membrane technology competitive compared to other technologies in various processes, such as separation, contacting process, reaction and catalysis, modification, and hybrid processes.^{5–8} An ion-exchange membrane (IEM) is a charged membrane that is mainly used to separate ionic species, such as in electrodialysis, dialysis, desalination, electro-oxidation, fuel cells, batteries, and so on.^{9–11} These processes have been applied in desalination and wastewater pretreatment, production of chloro-alkali chemicals, organic acid, organic salts, and ultrapure water by reverse osmososis and ion-exchange.^{12–14} With these various potential applications, IEM-based processes are considered to be the crucial processes in water and energy supply, the chemical industries, and environmental protection.

IEMs are generally classified into homogeneous and heterogeneous membranes regarding the structural heterogeneity.^{15–18} A homogeneous membrane only uses a single polymer to form a membrane structure and to provide functional or conductive parts. In contrast, a heterogeneous membrane has two different polymers: an inert polymer that acts as the membrane's structural matrix, and ion-exchange resin particles that provide active sites for ion transport. Generally, the heterogeneous IEM has a lower conductivity and permselectivity than the homogeneous because of its longer pathway for ionic migration, the presence of an inert fraction in the membrane phase, and leakage of an ions through a solution phase in the membrane.^{19–22} At the same time, the heterogeneous IEM has a better mechanical strength, easier preparation procedure, and lower production cost.^{23,24} Therefore, improving the electrochemical properties of heterogeneous IEM may be one of the ways to reduce the cost of IEM-based processes.

Several parameters of membrane preparation that determine the characteristics of the heterogeneous IEM have been reported in

Electrochemical Properties of Chemically Treated Polyvinylchloride-Based Heterogeneous Cation-Exchange Membrane

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Chemical treatment is a facile method for improving electrochemical properties of a heterogeneous ion-exchange membrane. In this work, poly(vinylchloride) (PVC)-based heterogeneous cation-exchange membrane is prepared by a dry-wet phase inversion process. The membrane is treated with a sulfonic acid solution in a room and a high temperature (80 °C). Effects of the treatment procedure and hydrophilic additive on membrane electrochemical properties are investigated. Chemically treated PVC and PVC/EGDE heterogeneous cation-exchange membranes allow a change in membrane electrochemical properties in terms of water uptake (WU), conductivity, ion-exchange capacity (IEC) and permselectivity (PS). In general, WU and conductivity increase after the chemical treatment. Significant improvement is observed when a high temperature is used. Meanwhile, the conductivity is more pronounced for PVC/EGDE membranes. The improvement may be associated with an increase in hydrophilicity. A significant increase in IEC is also observed for modified PVC/EGDE membranes. This may be associated with the removal or leaching of the additive during the treatment which in turn increases the portion of ion-exchange resin in the membrane. Most of the modified membranes show a decrease in λ . It may be due to a decrease in the effectiveness of Donnan effect indicated by Donnan equilibrium constant (K^+). POLYM. ENG. SCI., 134, 4699–4706, 2018 © 2018 Society of Plastics Engineers

INTRODUCTION

Ion-exchange membrane (IEM) is a charged membrane which is generally used for ionic separation such as in water treatment, wastewater treatment, product purification, chemical synthesis, and energy conversion [1–7]. Progress of IEM depends on its very large extent of diversity of IEM and chemical [8,9]. Commercial IEM is usually classified into homogeneous and heterogeneous membranes based on structure heterogeneity [10,11]. Despite the lower permselectivity and conductivity, heterogeneous IEM has better mechanical properties and lower production cost [12,13]. Therefore, preparation or modification of the heterogeneous IEM is needed to obtain efficient and cost-effective IEMs and processes.

The improved electrochemical properties can be achieved by several techniques such as sulfonic leaching, surface modification, chemical treatment, and thermal treatment. In sulfonic leaching, an

additive which is electrically conductive and hydrophilic and has functional sites is introduced into membrane matrix. Nonionic silicon, carbon nanotube, zeolite, and metal nitrate nanoparticles are the typical examples of the additive [14–20]. Compatibility between particle and membrane matrix, functional site blocking, and cracks are the main issues in particle leaching. Surface modification is carried out by depositing a oxidizer onto membrane surface or grafting [21–24]. Several works also use plasma treatment to modify IEM surface [25–27]. However, plasma treatment requires more complex equipment. Chemical and thermal treatments are other techniques which are reported by several works as effective methods for modification of heterogeneous IEM. As shown in a work conducted by Koyama et al. [28], permselectivity of membranes below the cation-exchange membrane was improved after heat treatment (at 200 °C for 10 min). The improvement was due to membrane structure densification. This is also reported by Shi et al. [29] on modification of heterogeneous cation-exchange membrane from blends of poly(ether sulfone)/sulfonated poly(ethylene oxide) and phenyl-phthalimide poly(ether ether ketone)/sulfonated poly(ethylene oxide). They also observed that electrical resistance and physical aperture of the membrane were minimal. Lopezova et al. [30] used polystyrene complex to chemically modify commercial membrane heterogeneous IEM. The chemical modifications reduced water desorption rate and increased membrane conductivity. VanZeyla et al. [31,32] reported the electrochemical properties and morphology of commercial heterogeneous cation- and anion-exchange membranes using a combined chemical and thermal treatment or thermal treatment. The membrane was immersed in a chemical solution and heated in a certain time. They found that the membranes showed higher electrical conductivities after the treatment. Meanwhile, membrane permselectivity was reduced. The change of electrochemical properties was due to the partial destruction of the membrane matrix, an increase in membrane hydrophilicity, and a reduction of membrane functional sites. Birkhoff et al. [33] investigated the effect of membrane acid-base properties on membrane electrochemical properties. Cation- and anion-exchange membranes were converted into H⁺ and OH⁻ ions. Na⁺ and Cl⁻ as multiple ions. They found that the activity selective procedure affected the electrochemical properties significantly. An efficient activity procedure depends on the treatment time and exchange agents.

Due to a relatively simple modification method, therefore, this work employs the chemical treatment to improve the electrochemical properties of the PVC-based heterogeneous cation-exchange membrane. The aim of this work is to study the electrochemical properties of PVC-based heterogeneous cation-exchange membrane after chemical treatment. PVC and PVC/EGDE membranes are chemically treated with a sulfonic acid solution by using three different procedures.

Structure and transport properties of polyvinyl chloride-based heterogeneous cation-exchange membrane modified by additive blending and sulfonation

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ABSTRACT

In this work, the structure-transport relationship of modified heterogeneous cation-exchange membrane (IEM) was investigated by the heterogeneous modification of poly(vinyl chloride) (PVC)-based IEM. IEMs were modified by a dry-wet hydrophilic additive and sulfonation in a sulfuric acid solution. The modified membrane was displayed a high degree of structure heterogeneity with lower phase number (Φ) of 1.23 to 1.32. The volume fraction of PVC (Φ_{PVC}) which is distributed in the prepared membranes has a relatively distributed conductive phase. In general, the lower phase number (Φ) has a positive effect on membrane conductivity. However, membrane permselectivity decreased higher than conductivity because. The addition of hydrophilic polymer to reduce the fraction of the gel phase and to reduce the water and ion transport increases the gel-phase conductivity (λ). Moreover, it has been found that permselectivity highly varies with λ .

1. Introduction

Ion-exchange membrane (IEM) has been used as a key to various electrochemical processes in water treatment, metal recovery, energy conversion and storage, fuel processing, and hybrid systems [1–7]. Commercially available IEMs are generally classified into homogeneous and heterogeneous membranes with their respective advantages and disadvantages [8,9]. The homogeneous membrane is simpler to prepare and has a lower production cost. It can be synthesized by depositing powder ion-exchange resin (IER) into polymer solution followed by phase inversion. However, heterogeneous membranes needs more sophisticated process to improve its conductivity and permselectivity.

The composition and material used in IEM preparation are important parameters that affect the electrochemical properties of the membrane. Poly(vinyl chloride) (PVC) is widely used as a main polymer of heterogeneous IEM because it has chemical resistance and reasonably good dimensional and mechanical properties [10]. In addition, PVC can bind IER particles well enough to produce a strong membrane structure. However, PVC tends to be hydrophobic as indicated by the water contact angle of the PVC film, which is around 130° [11] so that the resulting membrane conductivity is low. The hydrophilicity can be improved through sulfonation, surface modification, chemical, and thermal treatment [12,13].

The introduction of additive or additive blending media is a relatively simple membrane modification technique that can be used to improve the electrochemical characteristics of the heterogeneous membrane. Hydrophilic, charged, and conductive nanoparticles have been used for this purpose [20–23]. The additive helps the transfer of ions in the membrane matrix by forming membrane hydrophilicity, providing additional functional groups, or adding more conductive fraction. Conductivity and permselectivity of heterogeneous IEM can also be improved by surface modification methods, chemical treatment, and thermal treatment. For instance, heating heterogeneous IEM at 200 °C for 10 min has successfully increased its permselectivity [14]. It was demonstrated that the conductivity of a cation-exchange membrane can be increased after crosslinking improved in NaOH or H₂O₂ solution and heated at 100 °C for 50 h [15,16]. The improvement was associated with increasing membrane hydrophilicity and porosity. Improvements of PVC-based membrane properties by additive blending and chemical treatment were also reported in the previous studies [17,18].

Heterogeneity of membrane structure is one of the factors that influence the characteristics of IEMs. A heterogeneous membrane model has been proposed to determine the heterogeneity of the IEM structure [19]. In this model, the conductivity of IEM is a function of solid conductivity and conductive phase fraction. The conductive phase fraction is divided into gel phase (Φ) and non-gel phase fraction (Φ_c). The gel phase is a polymer

Improved anti-organic fouling of polyvinyl chloride-based heterogeneous anion-exchange membrane modified by hydrophilic additives

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ABSTRACT

Organic fouling— which generally gives a more severe effect on anion-exchange membrane (AEM)— leads to performance degradation of electro-membrane processes. In this work, poly(vinyl chloride) (PVC)-based AEMs were prepared by a solution casting method. These AEMs were modified by different hydrophilic additive, namely poly(ethylene glycol) 400 (PEG400), poly(vinyl alcohol) 200 (PVA200), and 2,6-diisopropyl-5(3-methylphenyl)-1,3,5-triazine (DPA-M). Then, the properties of these modified membranes were compared to the pristine membrane (M0 membrane). The effect of hydrophilic additive on the anti-organic fouling properties of modified membranes was investigated during a simple electrochemical test of feed water containing humic substances. The results of chemical structure analysis show that the additive was successfully incorporated in the membrane matrix. The presence of the hydrophilic additive in the membrane matrix increases membrane conductivity. The higher increase in conductivity is obtained by the addition of PEG400 (up to 20 %). Meanwhile, water uptake, ion-exchange capacity, and water contact angle of the modified membranes are insignificantly changed. In addition, the additive can improve membrane resistance toward organic fouling. The introduction of additive can suppress the increasing rate of membrane used resistance by ~40 %.

1. Introduction

Ion-exchange membrane (IEM) is a charged membrane that has a strategic role in the field of water treatment and energy storage or conversion. In water treatment, IEM-based processes such as electro-dialysis and demineralization, have been commercially applied in producing drinking water and industrial water [1]. However, their applications are limited by organic fouling when the feed water contains organic substances. Organic fouling occurs on anion-exchange membranes (AEM) due to the interaction between organic substances and the membrane charge [2]. AEM has found functional sites that are positively charged while organic substances such as humic are usually negatively charged [3, 4]. This makes organic substances are easily deposited on AEM surface. Organic substance-deposit increases membrane resistance to ions transfer through the membrane [5]. Consequently, the IEM-based process requires more energy to maintain a constant ion transfer rate if the fouling occurs. In addition, fouling leads to the decreasing membrane lifetime [6]. The low membrane lifetime will result in the high operational cost which is associated with membrane replacement.



Several strategies have been proposed to address fouling issues. Generally, fouling phenomena are controlled by providing an appropriate pre-treatment process, optimizing the process conditions, modifying membrane properties, and selecting suitable cleaning procedures [7]. One of the effective strategies is membrane surface modification which prevents fouling by altering membrane-fouling interaction [8]. Results from previous studies show that modifying membrane surface with materials that have negative charges or have high hydrophilicity can decrease organic fouling [9–12]. However, the addition of a new layer on the membrane surface will increase membrane thickness and the mass transfer resistance. Moreover, the addition of negatively charged layer, which is intended to reduce membrane-fouling electrostatic interaction, will restrict the permeation of anions through the AEM.

Another alternative way to improve membrane hydrophilicity is by introducing the additive into the membrane matrix. The incorporation

Ion-Exchange Membrane

Review paper

Surface modification of ion-exchange membranes: Methods, characteristics, and performance

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ABSTRACT: Considerable effort has been made to improve ion-exchange membrane (IEM) properties in order to achieve better performance of IEM-based processes in various applications. Surface modification is one of the effective ways to improve IEM properties. Various methods have been used to modify IEM surfaces, for example, plasma treatment, polymerization, solution coating, electrodeposition, and ion implantation. These methods are able to produce a thin and fine distributed layer and also to modify the chemical structure of the surface. The new layer can be adsorbed, deposited, or chemically bonded on a membrane surface. By using these methods, IEM properties are improved, and the desired or specific characteristics such as high monovalent ion permselectivity, low fuel crossover, and anti-organic-fouling property can be obtained. In this paper, methods for surface modification of IEMs are reviewed. Moreover, the effects of modification on IEM properties and performance are discussed. © 2017 Wiley Periodicals, Inc. *J Appl Polym Sci* 2017, 134, 45540.

KEYWORDS: conducting polymers; membranes; separation techniques; structure-property relationships

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INTRODUCTION

Membrane technology is widely developed due to its potential applications in almost every industrial sector.¹ Energy efficiency, high separation capacity, high selectivity, reduction in a number of unit processes, and relatively low cost are several advantages of membrane technology that make this technology competitive in various applications.^{1–10} An ion-exchange membrane (IEM) is a charged membrane that is used in electromembrane processes (e.g., electro dialysis, diffusion dialysis, electrolysis, electro-demineralization) as an ion-selective barrier and also as the key to the process.¹¹ IEM-based processes have found many applications in fields such as water and wastewater treatment, chemical synthesis, product purification and concentration, and energy conversion.^{12–17} For those various applications, IEMs are expected to have good separation properties (conductivity and permselectivity) and stability (mechanical, chemical, and thermal stability). Moreover, the development of IEMs is also directed at obtaining the membranes with lower fabrication cost and simpler procedures.

According to their structure, commercial IEMs are generally classified into two groups: homogeneous and heterogeneous.^{11,13,19} Methods for preparation of these types of membranes have been explained in the literature.^{20–25} In brief, a homogeneous IEM is usually prepared by using three different procedures: (1) polymerization or polycondensation of

monomers containing functional sites; (2) introduction of the functional groups into a polymeric film; or (3) casting of a polymer (that contains moieties) solution into a film.²⁶ Meanwhile, heterogeneous IEMs are prepared by combining ion-exchange resin powder and polymeric resin (mostly inert polymer) into a film.^{26,28} Usually, heterogeneous IEMs exhibit lower conductivity due to the presence of a nonconductive phase and lower selectivity due to less efficacy of Donnan exclusion in the intergel phase (the gap between the inert polymer and the ion-exchange resin filled by solution) inside the membrane matrix.^{26,28} However, heterogeneous IEMs have relatively high mechanical and chemical stability, a simpler preparation procedure, and relatively lower production cost than the homogeneous membranes.^{26,28}

Nevertheless, there are still several limitations hindering the applications of those commercial IEMs, including low permselectivity, high areal resistance, relatively low monovalent permselectivity, fouling of organic components on an anion-exchange membrane, and relatively high fuel crossover (e.g., methanol).^{26–30} Therefore, improvements of IEM properties are required to achieve better performance. There are several strategies that can be used for improving the properties of IEMs, such as materials selection, introduction of an additive that has specific property, and surface modifications of the prepared membrane.¹⁸ There is considerable evidence that a properly

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45540 [1 of 13]

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Heterogeneous structure and its effect on properties and electrochemical behavior of ion-exchange membrane

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Keywords: membrane; ion-exchange membrane; ionic transfer; electrochemical properties; ion separation

Abstract

Generally, commercially available ion-exchange membrane (IEM) can be classified into homogeneous and heterogeneous membranes. The classification is based on degree of heterogeneity in membrane structure. It is well known that the heterogeneity greatly affects the properties of IEM, such as conductivity, permselectivity, chemical and mechanical stability. The heterogeneity also influences ionic and electrical current transfer behavior of IEM-based processes during their operation. Therefore, understanding the role of heterogeneity in IEM properties is important to provide preliminary information on their operability and applicability. In this paper, the heterogeneity and its effect on IEM properties are reviewed. Some models for describing the heterogeneity of IEM and methods for characterizing the degree of heterogeneity are discussed. In addition, the influence of heterogeneity on the performance of IEM-based processes and their electrochemical behavior are described.

1. Introduction

Membrane technology has been widely applied and started to replace conventional technology in a number of processes such as molecular filtration [1, 2], contacting process [3–5], hybrid process [6], etc, due to advantages of membrane technology including energy efficiency, high separation capacity, selective separation, reduced unit processes, and low investment cost. IEM is a charged membrane which is mainly used in separation of ionic components. IEM is used as a key of several separation processes such as electro dialysis, electrolysis, diffusion dialysis, electrodeionization, fuel cells, reverse electro dialysis, etc. Those processes have been applied in various fields of applications including water treatment [7, 8], wastewater treatment, chemical synthesis [9], product purification [10, 11], and energy generation [12].

Since IEM is the key of the separation processes, it is expected to have high conductivity, high counter-ion permselectivity, and good mechanical and chemical stability to improve the applicability and operability in various conditions. Moreover, the development of IEM is also directed to obtain the membranes with lower production cost and easier preparation procedure. IEM with improved characteristics could be achieved by several strategies, such as selection of the appropriate materials, incorporation of additive which has specific properties, modification of membrane surface, and chemical and thermal treatment of the prepared membrane [13]. It is well known that membrane surface and morphology play an important role in the performance of membrane separation processes. In the case of IEMs, the presence of heterogeneous structure and its effect has been investigated in numerous works. In this paper, the effect of heterogeneity on IEM properties and transport behavior are reviewed to provide a better understanding about the role of heterogeneity in IEM.

2. Homogeneous and heterogeneous IEMs

Commercially available IEM can be classified into two major groups, which are homogeneous and heterogeneous IEMs [9]. This classification is based on the structure of the membranes that is the homogeneity or the heterogeneity of the membrane structure (see figure 1). In homogeneous IEMs, a polymer is used to form a membrane structure and also to carry functional sites needed for ions transport [14]. Meanwhile, for heterogeneous IEMs, two different polymers are involved. The first polymer acts as structural former or matrix polymer. The second polymer, which is usually a finely ground ion-exchange resin, is used to carry the functional sites [14]. Since the first polymer used in

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Reverse Osmosis

Review paper

Desalination 391 (2016) 112–125

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Reverse osmosis applications: Prospect and challenges
I.G. Wenten*, Khoiruddin
Department of Chemical Engineering, ITS, Ganesha 10, Bandung 40132, Indonesia

HIGHLIGHTS

- Applications of reverse osmosis (RO) membrane are reviewed.
- Advantages and limitations of the applications are discussed.
- Challenges and perspective are pointed out.

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ABSTRACT

Reverse osmosis (RO) is a pressure driven membrane process which has been widely applied and recognized as the leading technology of desalination process. Improvement in RO technology including advanced membrane material, module and process design, and energy recovery has led to cost reduction which in turn gaining interest in its commercial applications. RO is now being used in various applications including selective separation, purification, and concentration processes. In food industry, RO is applied for concentration of fruits and vegetable juices, pre-concentration of milk and whey, and dealkoholization of alcoholic beverage. For area which has large source of natural brackish water or post water, RO can be applied to produce clean water for community water supply. RO was also investigated for organic mixture separation and CO₂ regeneration from essential oil extraction using supercritical fluid. The application of RO as a final step of wastewater treatment for water reuse and high strength wastewater recovery seems to be promising in wastewater reclamation. In this paper, the applications of RO, its advantages, and limitations are discussed. In addition, challenges and perspective of RO membranes are pointed out.

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1. Introduction

Rapid growth in membrane technology development is primarily based on consciousness on the potential of this technology. Membrane processes have many advantages allowing various applications in almost every industrial sector. The major breakthrough in the development of membrane technology was recorded in the late 1950s, when Sartorius Werke GmbH, Germany manufactured industrial scale membranes and microfiltration membranes, for the first time. However, industrial application was just started ten years later, when Loeb and Sourirajan discovered very thin membrane for reverse osmosis (RO), the asymmetric membranes for seawater desalination.

RO system separates dissolved solutes (includes single charged ions, such as Na⁺, Cl⁻) from water via a semipermeable membrane that passes water in preference to the solute. RO can be described as a diffusion-controlled process in which the mass transfer of permeant through RO membranes is controlled by diffusion known as solution-diffusion mechanism. In the solution-diffusion mechanism, permeants dissolve in membrane material and then diffuse through the membrane [1]. RO membrane is very hydrophilic; therefore water will be able to readily diffuse into and out of the membrane polymer structure.

RO system can be found today in a wide range of facilities: kitchen, hospitals, refineries, power plants, pulp and paper industries, crude palm oil milling, semiconductor manufacturing facilities, marine spacecraft, sailboats, etc. RO is used as a concentration step particularly in food industry, galvanic industry, and dairy industry [2]. Improvement in RO technology such as membrane material, module and process design, pre-treatment, and energy recovery has led to cost reduction that drives the interest in its commercial applications [3]. RO is now being used for various applications both for purification and concentration and becomes a leading technology for brackish and seawater desalination. In this paper, the applications of RO are pointed out including water treatment, wastewater treatment, food and beverage processing, organic mixture separation, and other applications. In the last part, challenges and perspectives in RO process are discussed.

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Article

Reverse osmosis applications: Prospect and challenges

Wenten, I.G., Khoiruddin

Desalination, 2016, 391, pp. 112–125

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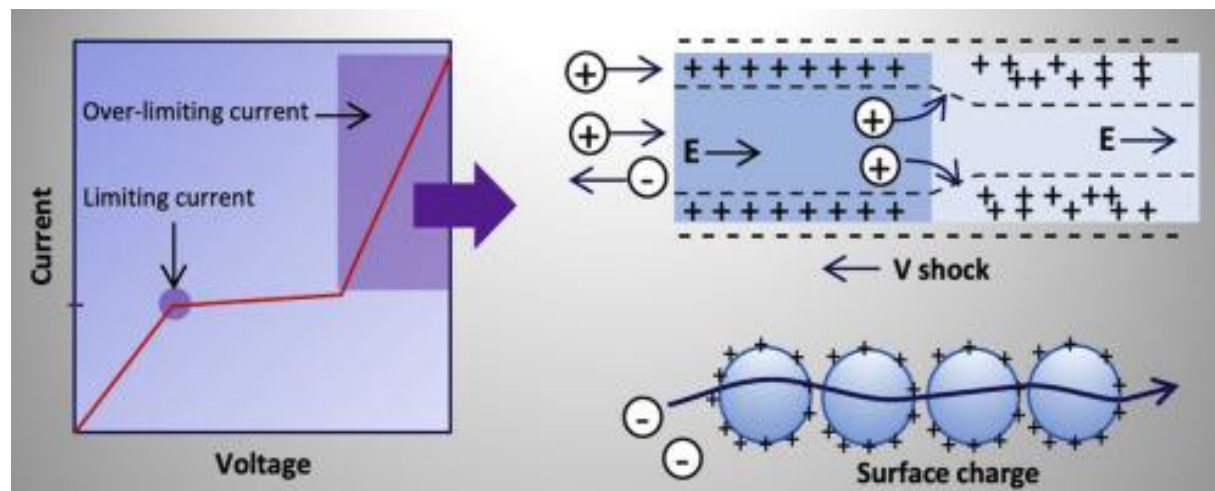
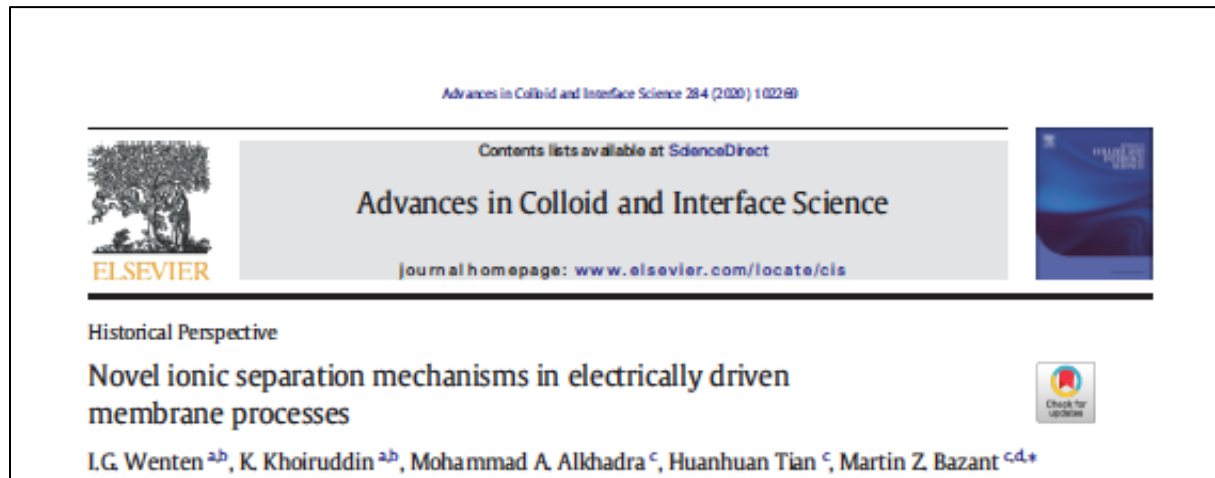
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“In my lab, we start by asking: what is the purpose of this review? My reasons for writing one can include the chance to contribute insights to the scientific community and identify opportunities for my research.”

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- Electrodeionization (EDI)
- Shock electro dialysis (SED)

Menyusun Paper Review: Menentukan Topik (2)

Separation & Purification Reviews, 0: 1–23, 2019
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ISSN: 1542-2119 print / 1542-2127 online
DOI: <https://doi.org/10.1080/15422119.2019.1608562>



Ionic Separation in Electrodeionization System: Mass Transfer Mechanism and Factor Affecting Separation Performance

A.N. Hakim,^{*1} K. Khoiruddin,¹ D. Ariono,¹ and I.G. Wenten^{1,2}

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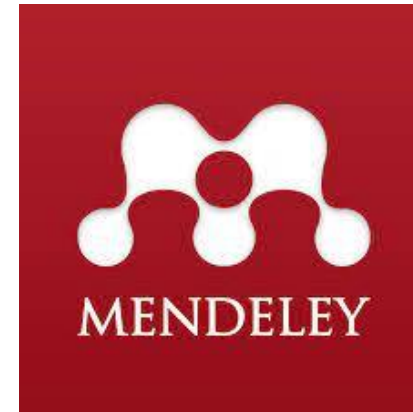
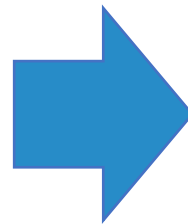
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Star	Authors	Title	Year	Published In	Added
☆	Alkhadra, Mohammad; Su, Xiao; Suss, Matthew; Tian, Huanhuan; Guyes, Eric; S...	Electrochemical Methods for Water Purification, Ion Separations, and Energy Conversion	2022	Chemical Reviews	Jul 7
☆	Rathi, B S; Kumar, P S; Parthiban, R	A review on recent advances in electrodeionization for various environmental applications	2022	Chemosphere	Jan 4
☆	Soysüren, G; Yetgin, A G; Arar, Ö; Arda, M	Removal of manganese (II) from aqueous solution by ionic liquid impregnated polymeric sorbent and electrodeionization (EDI) techniques	2022	Process Safety and Environmental Protecti...	Jan 4
☆	Erol, H B U; Hestekin, C N; Hestekin, J A	Effects of resin chemistries on the selective removal of industrially relevant metal ions using wafer-enhanced electrodeionization	2021	Membranes	Jan 4
☆	He, Jian-cheng; Jia, Yu-xiang; Yan, Ru; Wang, Meng	An electrodialysis-based coupling technique for simultaneous reclamation of waste acid and cleaner production of organic acid	2021	Journal of Membrane Science	Jul 26
☆	Julian, Helen; Khoiruddin, K; Julies, Nia; Edwina, Vinka; Wenten, I G	Pineapple juice acidity removal using electrodeionization (EDI)	2021	Journal of Food Engineering	30/03/21
☆	Khoiruddin, Khoiruddin; Hakim, Ahmad; Bazant, Martin; Alkhadra, Mohammad; W...	SMALL-SCALE SEAWATER ELECTRODEIONIZATION	2021	Authorea Preprints	Jan 20
☆	Kingsbury, R S; Coronell, O	Modeling and validation of concentration dependence of ion exchange membrane permselectivity: Significance of convection and Manning's counter...	2021	Journal of Membrane Science	27/12/21
☆	Otero, C; Urbina, A; Rivero, E P; Rodríguez, F A	Desalination of brackish water by electrodeionization: Experimental study and mathematical modeling	2021	Desalination	Jan 4
☆	Rathi, B S; Kumar, P S	Continuous electrodeionization on the removal of toxic pollutant from aqueous solution	2021	Chemosphere	Jan 4
☆	Sarıççek, E N; Tuğaç, M M; Özdemir, V T; İpek, İ Y; Arar, Ö	Removal of boron by boron selective resin-filled electrodeionization	2021	Environmental Technology and Innov...	Jan 4
☆	Zhang, X; Deng, S; Jin, H; Yu, Y; Liao, S; Chen, X	Synthesis and characterization of an amphoteric resin for use in membrane-free electrodeionization	2021	Separation and Purification Technology	Jan 4
☆	Alkhadra, Mohammad A; Gao, Tao; Conforti, Kameron M; Tian, Huanhuan; B...	Small-scale desalination of seawater by shock electrodialysis	2020	Desalination	27/12/21
☆	Chen, Qing-Bai; Wang, Jianyou; Liu, Yu; Zhao, Jinli; Li, Pengfei	Novel energy-efficient electrodialysis system for continuous brackish water desalination: Innovative stack configurations and optimal inflow modes	2020	Water Research	Oct 23
☆	Hakim, A N; Khoiruddin, K; Ariono, D; Wenten, I. G.	Ionic separation in electrodeionization system: Mass transfer mechanism and factor affecting separation performance	2020	Separation & Purification Reviews	22/11/20
☆	Jordan, M L; Valentino, L; Nazrynbekova, N; Palakkal, V M; Kole, S; Bhattacharya, D...	Promoting water-splitting in Janus bipolar ion-exchange resin wafers for electrodeionization	2020	Molecular Systems Design and Engineering	Jan 4
☆	Jordan, Matthew L; Valentino, Lauren...	Promoting water-splitting in Janus bipolar ion-exchange resin wafers for...	2020	Molecular Systems...	Feb 16

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Knowledge Map of ion-exchange membrane

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journal/newspaper article

The effect of organic ion-exchange resin on properties of heterogeneous ion-exchange membranes (2010)

J. Křivčík, J. Vladařová, J. Hadrava, A. Černín, L. (Libuše) Brožová
[doi]: <https://doi.org/10.5004/dwt.2010.1025>

This case study deals with relationships between characteristic properties of organic ion-exchange resins and heterogeneous ion-exchange membranes. Membranes were prepared by using different filler/polymer matrix ratio or by using milled resins with different particle size...

Cite as Export

Area: Heterogeneous ionexchange membranes, Ionexchange resin particles, Ionově výměnné část...

journal/newspaper article

Increasing selectivity of a heterogeneous ion-exchange membrane (2015)

J. Křivčík, D. Neděla, J. Hadrava, L. (Libuše) Brožová
[doi]: <https://doi.org/10.1080/19443994.2014.980970>

Selectivity, permselectivity, and conductivity are the main ion-exchange membrane parameters. While permselectivity determines how well the membrane separates cations from anions, the selectivity determines how well the membrane transports uni- and multivalent ions...

Cite as Export

Area: Ionexchange membranes, Permselectivity, Electrodialysis

journal/newspaper article

Reinforcing fabrics as the mechanical support of ion exchange membranes (2017)

Eliška Stránská, David Neděla

The knowledge map on the left features several interconnected nodes, including: Microbial fuel cell, Composite membrane, Ion exchange membrane, Aniline-2-sulfonic acid; Amphiuma tri-dactylum, Erythrocyte membrane, Actuator; Sulfonated polysulfone bentonite, Electrolyte membrane, ...; Anion exchange membrane, Cation exchange membranes, Electric potential; Electrodeionization, Groundwater treatment, International development; Penicillin g amidase, Cell lysate, Analytical Biochemistry; Hybrid ionexchange membranes, Assembled sulfonated, Electrical resistance; Acid membrane, Alginate, Ceram membrane; Ionexchange membranes, Permselectivity, Electrodialysis; Heterogeneous ionexchange membranes, Ionexchange resin particles, Ionově...; and Hybrid process, Boron removal, Geothermal water.

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Outline

Highlights

Abstract

Keywords

1. Introduction
2. Water treatment
3. Wastewater treatment
4. Food and beverage processing
5. Organic mixture separation
6. Other applications
7. Challenges and perspective



Desalination
Volume 391, 1 August 2016, Pages 112-125



Reverse osmosis applications: Prospect and challenges

I.G. Wenten  , Khoiruddin

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1. Introduction
2. Enhanced ion transport by electroconvection and elect...
3. Ion transport in micro/nanofluidic systems
4. Deionization shock waves
5. Shock electrodialysis (shock ED)
6. "Ionic bridges" for deep deionization in electrodeioniz...
7. Conclusion and future outlook



Advances in Colloid and Interface Science

Volume 284, October 2020, 102269



Historical Perspective

Novel ionic separation mechanisms in electrically driven membrane processes

I.G. Wenten ^{a, b}, K. Khoiruddin ^{a, b}, Mohammad A. Alkhadra ^c, Huanhuan Tian ^c, Martin Z. Bazant ^{c, d}  

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Menyusun Paper Review: Menyusun Struktur Paper (3)

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The image shows the cover of a review article. At the top left is the logo for 'JOURNAL OF Applied Polymer SCIENCE' in purple. To the right of the logo is the word 'REVIEW' in black. Below the logo is a horizontal purple line. Underneath the line is the title 'Surface modification of ion-exchange membranes: Methods, characteristics, and performance' in bold black text. Below the title are the authors' names: 'Khoiruddin', 'Danu Ariono', 'Subagjo', and 'I Gede Wenten', each followed by a small green ID icon.

- Introduction
- Ion-exchange membrane and their applications
- Surface modification methods
- Surface-modified ion-exchange membranes
- Conclusions and future outlook

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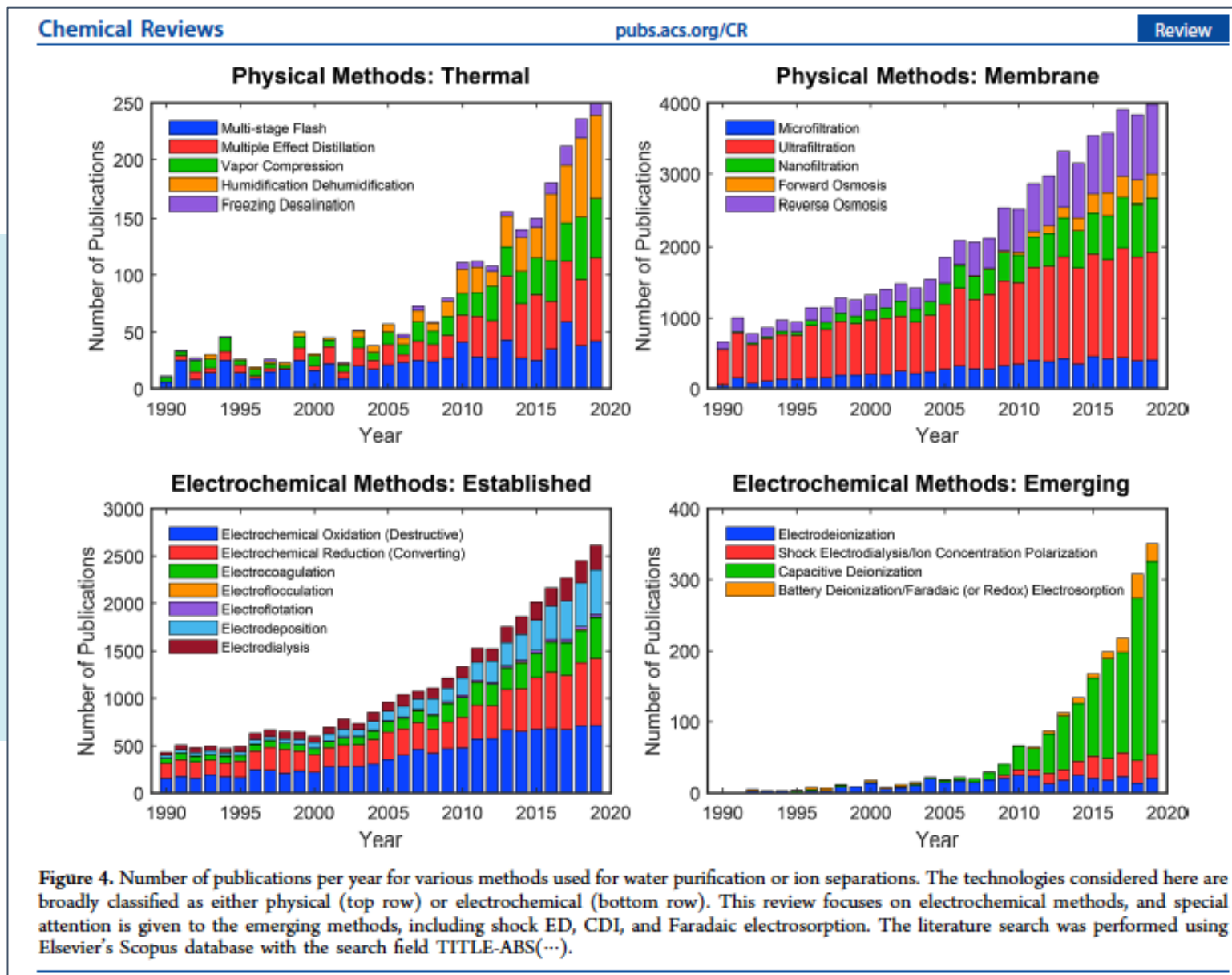


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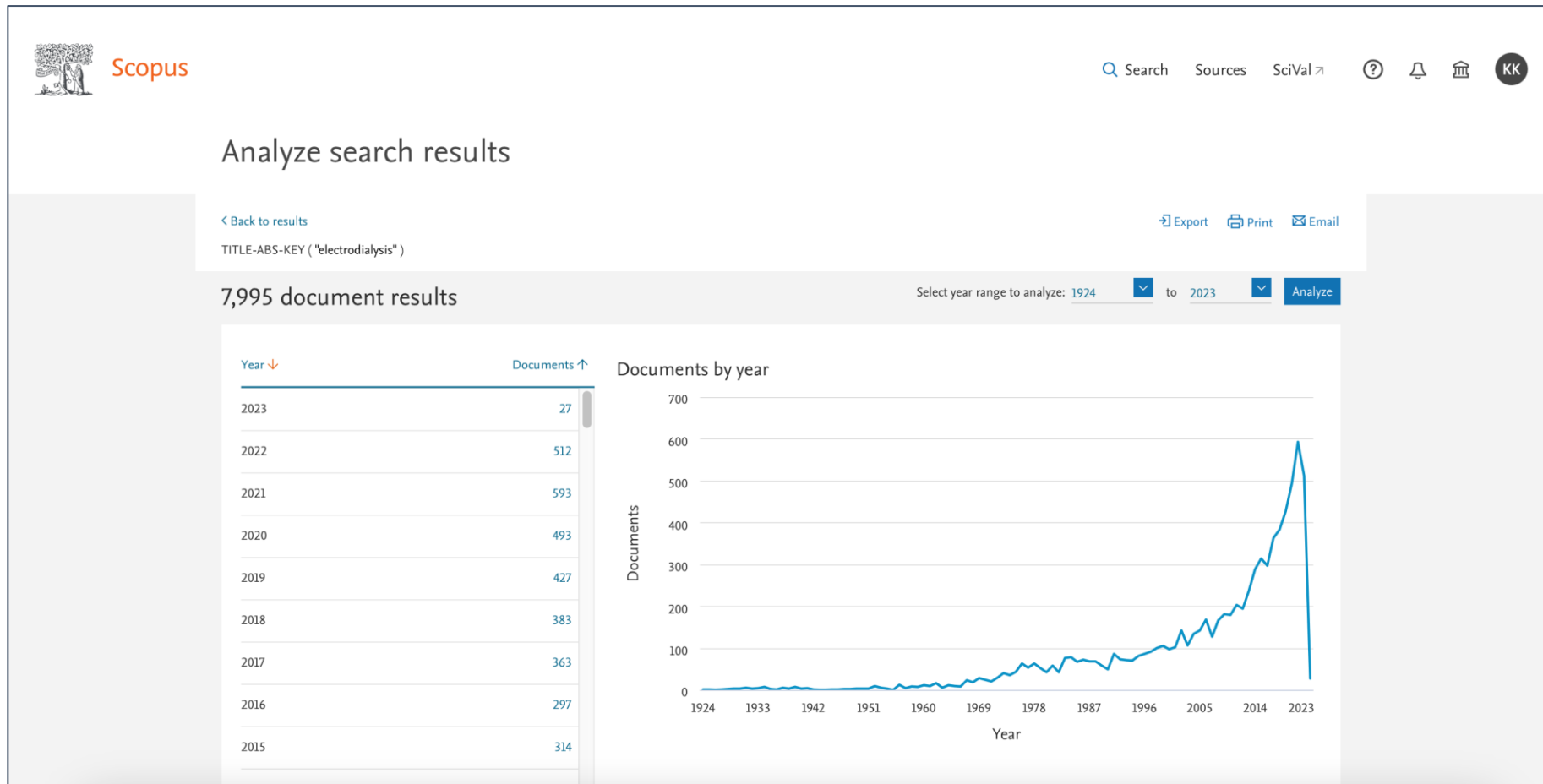
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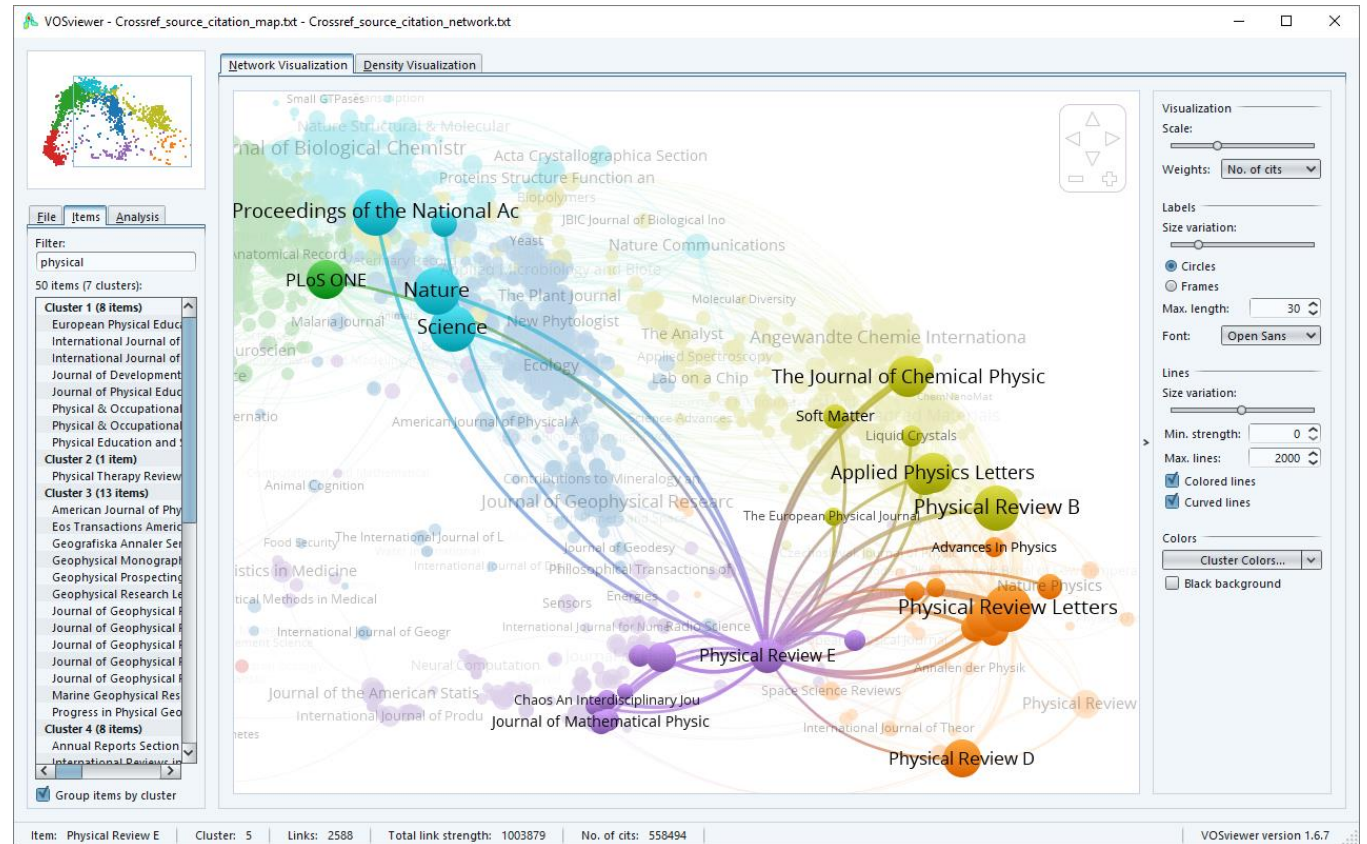
Menyusun Paper Review: Gambar dan Tabel (1)



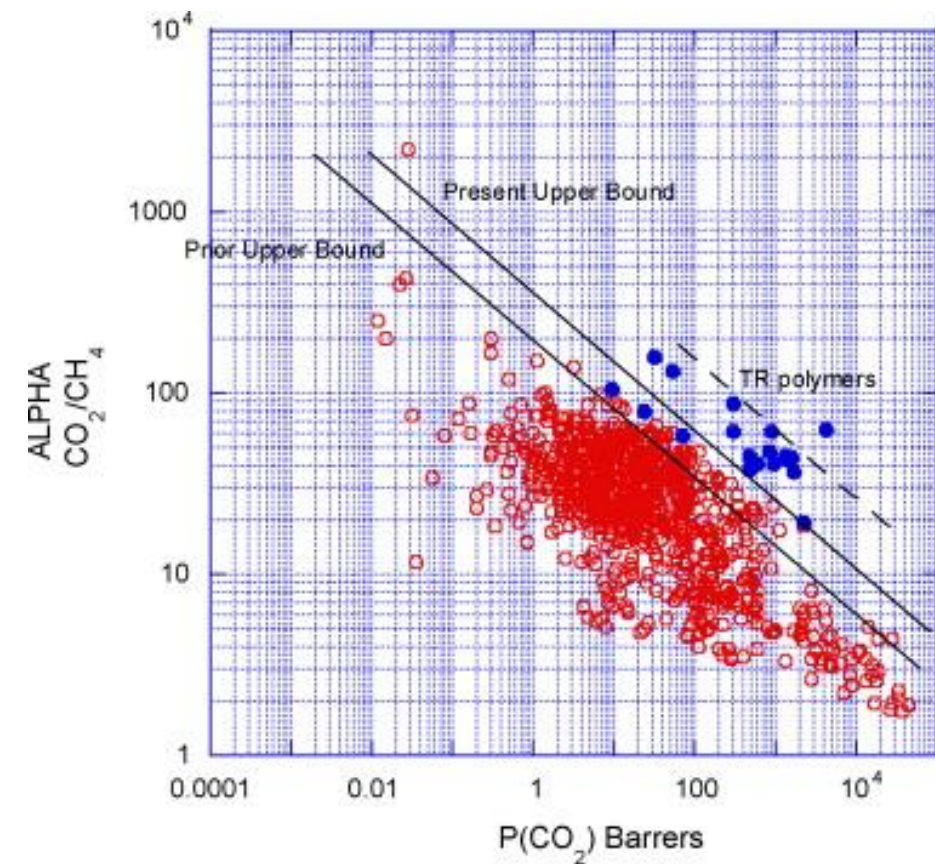
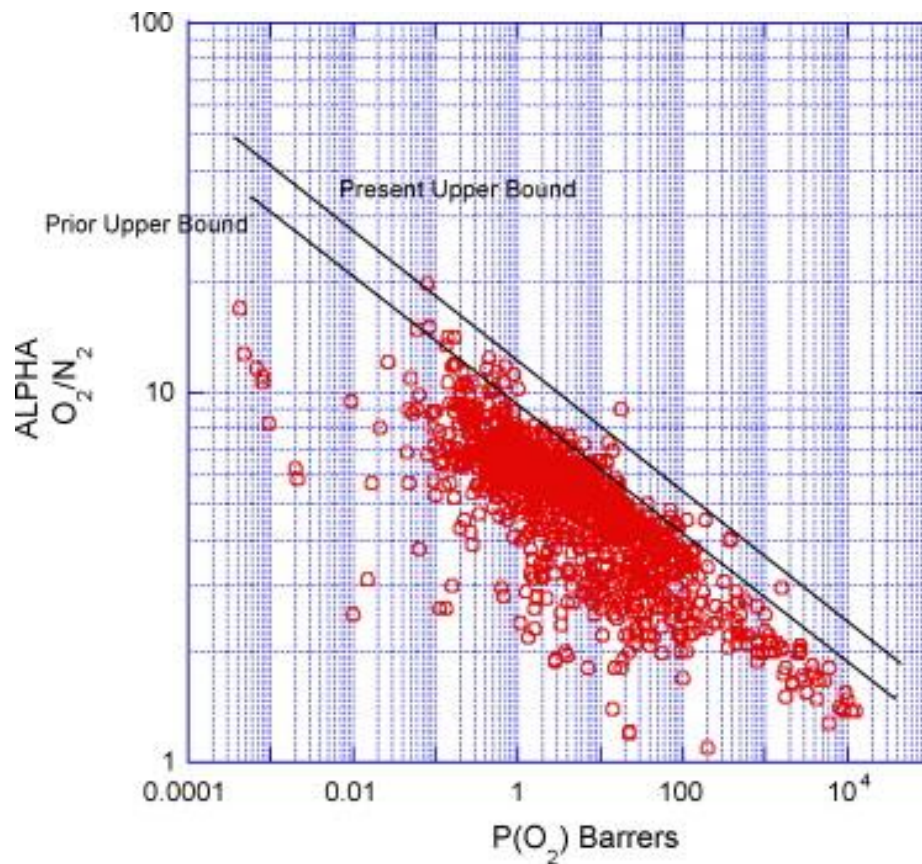
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Menyusun Paper Review: Gambar dan Tabel (3)

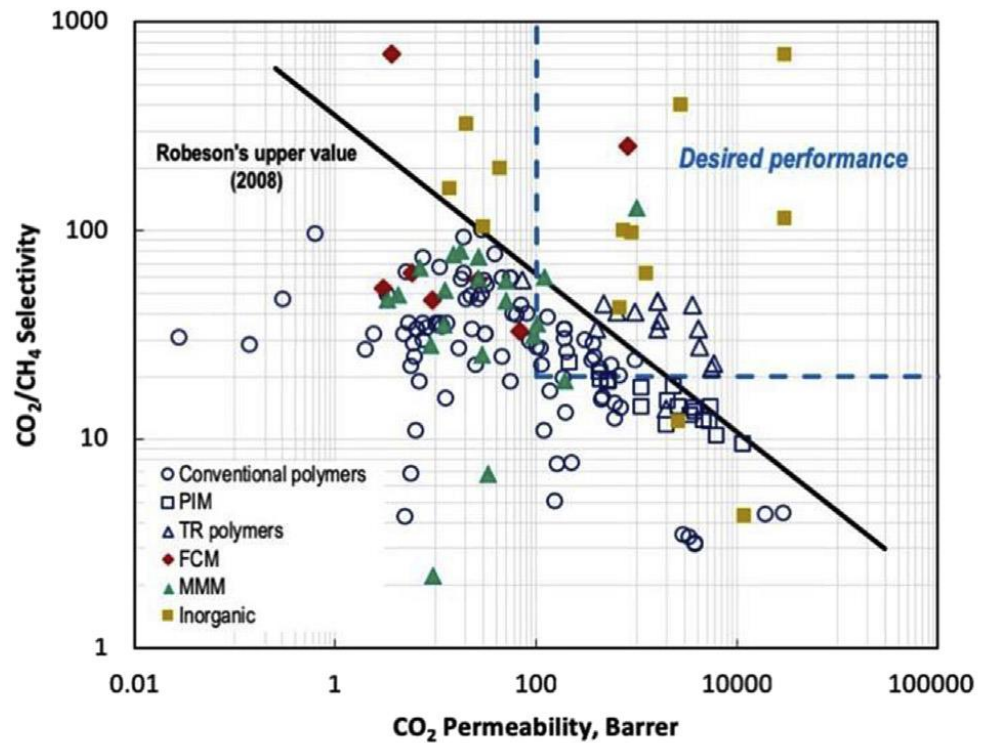


Menyusun Paper Review: Gambar dan Tabel (5)

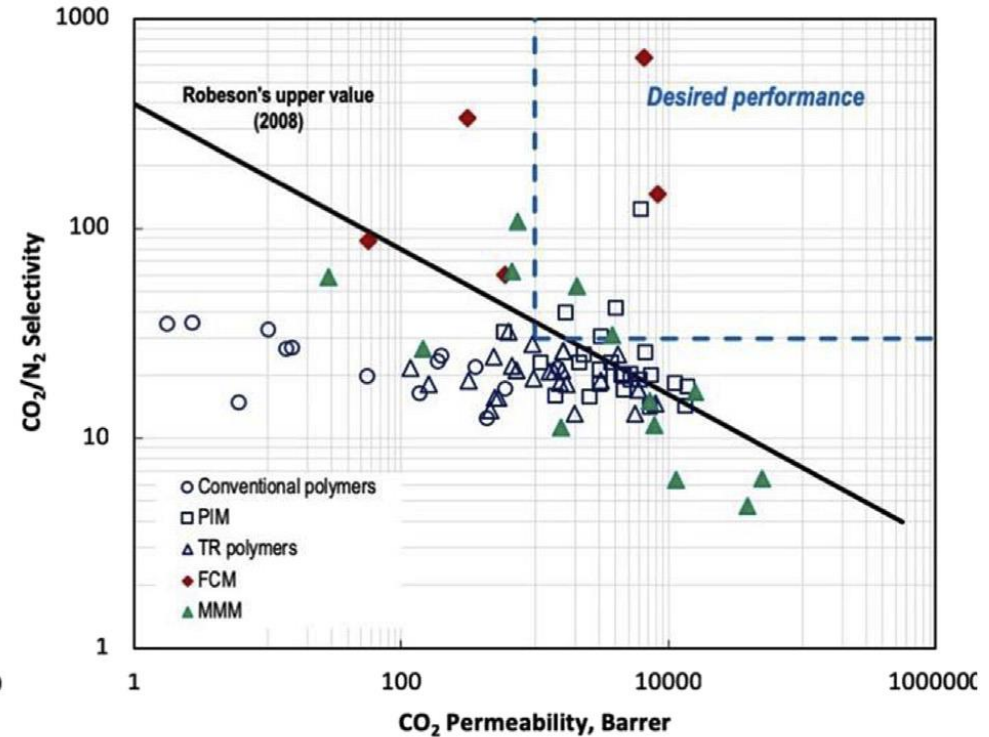


Robeson (2008). *Journal of membrane science*, 320(1-2), 390-400.

Menyusun Paper Review: Gambar dan Tabel (6)



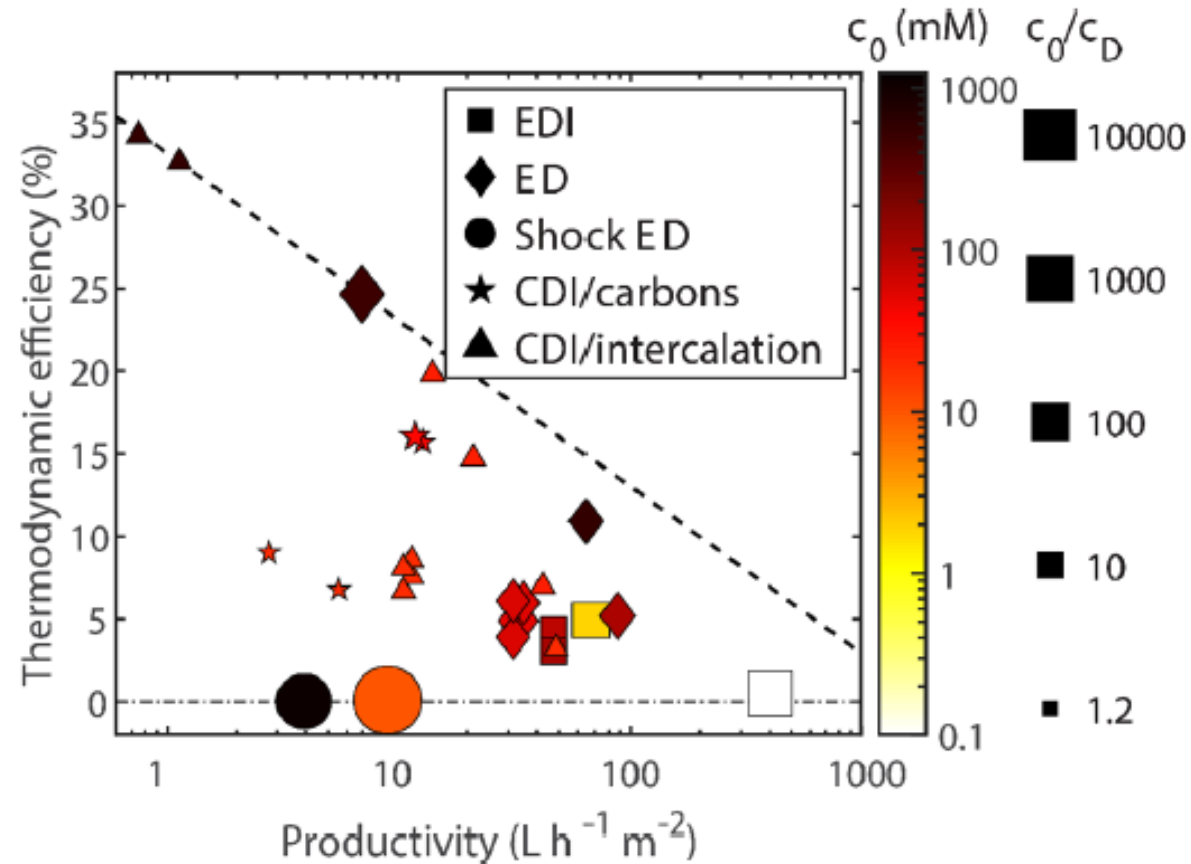
(a)



(b)

Siagian et al., Journal of Natural Gas Science and Engineering 67 (2019) 172–195

Menyusun Paper Review: Gambar dan Tabel (7)



Alkhadra et al., Chemical Reviews, 122(16), 13547-13635.

Menyusun Paper Review: Gambar dan Tabel (8)

Table II. Features of Several Modified Surfaces

Modified surface	Characteristics	Features	Ref.
Anion-exchange layer (cationic charged layer)	Provides an electrostatic repulsion for multivalent cations	Improvement of proton and monovalent cation permselectivity	34,53,73
Cation-exchange layer (anionic charged layer)	Provides an electrostatic repulsion for multivalent anions	Improvement of monovalent anion permselectivity	53
Sulfonamide groups	Decreases the ionic nature of the surface	Less water transport, high cation permselectivity	37
PEI layer	Provides an electrostatic repulsion for multivalent anions	Improvement of monovalent anion permselectivity	74,75
Crosslinked and protonated chitosan layer	Rigid and less hydrophilic	Reduction of methanol crossover	60
Aminated and sulfonated polysulfone layer	Rigid layer	Reduction of methanol crossover	57
Plasma-treated membrane (gas plasma)	Improved hydrophilicity	High ionic permeability	48,49
Polypyrrole layer	Good repelling property to cations	Improvement of metal-repelling property, retained high acid permeability	67
PSS and poly(allylamine hydrochloride)	High hydrophilicity	Improvement of monovalent selectivity and anti-organic-fouling property	72
BPPO layer	Hydrophobic, compact, ion-selective barrier, noncharged layer	Reduction of metal crossover	63
MF-4SK film	Hydrophobic, homogeneous	Enhancement of mass transfer	62
Silver nanolayer	Electrically conductive, antibacterial	Enhancement of electrochemical properties, antibacterial property	32

Khoiruddin et al., Journal of Applied Polymer Science, 134(48), 45540.

Menyusun Paper Review: Gambar dan Tabel (9)

Table 1

Equations for the estimation of the diffusion limited current (DLC, I_{lim})

No.	Equations	Parameters	Experimental conditions	Ref.
1.	$I_{lim} = FDC / (t\delta)$	F = Faraday's constant D = diffusion coefficient of salt C = concentration of monovalent salt t = transport number of coions in bulk solution δ = thickness of diffusion layer	Feed = 0.01 M NaCl.	[33]
2.	$I_{lim} = FDC / [(t_m - t_s) \delta_L S]$ $S = \kappa_m / (\kappa_0 \tau)$	S = true surface conductivity of heterogeneous membrane t_m = transport number of ion in membrane t_s = transport number of ion in solution δ_L = thickness of diffusion layer formed by heterogeneous membrane κ_m = conductivity of heterogeneous membrane κ_0 = conductivity of pure ion exchange resins τ = tortuosity of channels in heterogeneous membrane	Feed = 0.1 M NaCl; velocity = 2 cm/min;	[34]
3.	$Sh = [0.095 / (t_m - t_s)] [n (t-d)]^{-1/2} [(1-\epsilon)^2 / \epsilon^3]^{1/5} (H/L)^{1/3}$ $M^{1/3} Re^{1/2} Sc^{-1/3}$ $Sh = H I_{lim} / (CDF)$	d = diameter of fiber in the spacers H = compartment thickness L = length of the compartment M = a parameter which is a function of spacers parameters: $f(n, t, d, \epsilon)$ n = number of spacers Sh = Sherwood number Re = Reynold number Sc = Schmidt number ϵ = spacer porosity	Spacer types: honeycomb and pointed twill spacers. Compartment thickness = 1.5–4.0 mm; Feed = 0.05 M NaCl	[36]
4.	$I_{lim} = C u^{1/3} 1.15 \times 10^5 \exp(-2.28 \times 10^3 / T + 273)$	T = temperature condition	T = 15–90 °C; NaCl concentration = 0.005–0.03 M; linear velocity = 0.206–2.44 cm/s;	[37]
5.	$I_{lim} = a u^b C$	a, b = parameters of stack design that are determined experimentally C = solution concentration in diluate compartment u = liner velocity	ED with 6 mm flow cell thickness; 0.017–0.05 m/s flow velocities; 0.008–0.1 M NaCl solution.	[26,38]
6.	$I_{lim} = \alpha Q_p^\beta$	Q_p = volumetric flow rate of product $\alpha = 2.63 \pm 0.04$ for salt concentration < 6000 mg/L and 4.01 ± 0.08 for salt concentration 6000–8000 mg/L $\beta = -0.51$	Flow cell thickness = 1 mm; velocity = 2–7 cm/s; NaCl concentration = 3330 mg/L and 7190 mg/L;	[40]
7.	$I_{lim} = (m_1 + m_2 u_{out}) C_{out}^{m_1+m_2} u_{out}$	C_{out} = concentration of diluate u_{out} = linear velocity of diluate m, n = constants	Cell thickness = 0.75 mm; velocity = 1.6–13.6 cm/s; NaCl concentration = 1×10^{-5} to 1×10^{-4} M;	[41,42]
8.	$I_{lim} = F (k_{eff} / D_{eff}) \left[\sum_{j=1}^n C_{j\beta} / \sum_{j=1}^n (t_{j,lim}^n / (z_j D_j)) \right]$	D_{eff} = effective diffusivity of several ions k_{eff} = effective mass transfer coefficient of multi-ions z = valence of ions	Spacer thickness = 0.77 mm; velocity = 0.066–0.11 m/s; solutions: 5×10^{-3} M $MgSO_4$ + 5×10^{-3} M $MgCl_2$ and 1×10^{-2} M $MgSO_4$ + 1×10^{-2} M $MgCl_2$;	[39]

Wenten et al., Advances in Colloid and Interface Science 284 (2020) 102269

Menyusun Paper Review: Belajar dari Reviewer (1)

1

"Membrane parameters and membrane quality in different sub-sections should be explained in more detail and discussed. In this way, experts working on membranes will get prior idea and insights to select the required (proper) membrane."

2

"The authors should clearly highlight key bottlenecks in the development of ..."

3

"Also, discuss factors affecting the performance of ..."

Menyusun Paper Review: Belajar dari Reviewer (2)

4

"... et al., also used ceramic membrane in ... and ... it will be better to mention ceramic membrane in the membrane discussion part. "

5

"How about the Copper, Nickel and Cobalt removal?"

6

"Only TFC membranes are discussed; Asymmetric cellulose acetate membranes should be discussed as well. "

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Terima kasih.

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