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Pervaporative desalination of high-salinity water

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ABSTRACT

Desalination of high salinity water by pervaporation using hydrophilic poly(ether-block-amide) membranes was investigated. A flux of 1680 g/(m² h) and almost complete salt rejection (>99.9%) were achieved at 65 °C. Increasing salt concentration from 1 to 20 wt% resulted in a 50% reduction in water flux, whereas the salt rejection was not influenced. The salt rejection was not influenced by the salt type (i.e., NaCl, MgCl₂ or Na₂SO₄) either. With an increase in temperature, the water flux through the membrane increased in spite of a decrease in the water permeability coefficient. The temperature dependence of water flux obeyed an Arrhenius type of relationship. Batch operation over a period of 10 h showed that the water flux decline could be recovered by washing the membrane with deionized water and there was no irreversible fouling during the pervaporative desalination process.

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1. Introduction

Water scarcity has become nowadays one of the most serious challenges globally in our society. To solve the water shortage issues, various desalination processes have been developed and they can be divided into two main categories: thermal processes (e.g., multi-stage flash distillation (MSF) and multiple-effect distillation (MED)), and membrane-based non-thermal processes (e.g., reverse osmosis (RO), membrane distillation (MD) and pervaporation (PV)). Compared to the thermal processes, the membrane separation processes have become a popular choice for water desalination because of its high separation efficiency and operational stability, low energy and chemical consumption, as well as ease of control and integration with other processes (Drioli et al., 2011). Currently, RO accounts for 60% of the desalination capacity for sea water and brackish water.

In reverse osmosis, a pressure is applied to the feed water in order to overcome its osmotic pressure so as to pass water through the membrane, and thus the energy consumption for feed water pumping will become increasingly important when dealing with high salinity water. In addition, a pre-treatment is often required for RO because it is prone to membrane fouling, which will lower the membrane performance. In general, the water recovery in RO systems ranges from 35% to 85% (Pérez-González et al., 2012), and the retentate stream with concentrated saline water will probably cause a secondary pollution (Wang

et al., 2014). Therefore, such alternative membrane technologies as membrane distillation (MD) and pervaporation (PV) have also been proposed for use in water desalination under certain niche conditions. In MD for water desalination, a hydrophobic microporous membrane is usually used as a barrier to prevent feed liquid from entering the pores while allowing the water vapor to pass (Fig. 1(a)). On the contrary, pervaporative desalination is normally carried out using a hydrophilic dense membrane or molecular sieving membrane that preferentially permeates water molecules. The permeate water vapor is allowed to condense on the downstream of the membrane and collected as purified water (Fig. 1(b)). Both processes tend to have a low energy consumption as they do not need to overcome the high osmotic pressure. In addition, they both can achieve a near 100% salt rejection regardless the salt concentration in the feed water (Drobek et al., 2012). However, in MD, membrane wetting may occur during prolonged uses, which leads to a decrease in the membrane hydrophobicity and consequently a reduction in salt rejection (García-Payo et al., 2000). Moreover, the colloidal and particulate matters, macromolecules and microorganisms present in the feed solution can be easily deposited on the MD membrane surface due to its hydrophobicity, and this will result in surface fouling and even plugging of the membrane pores which in turn increases the chance of membrane wetting (Tijing et al., 2015). Membrane fouling and wetting are the main challenges in MD processes. Such problems are usually not as severe in PV since hydrophilic PV membranes tend to have much better anti-fouling properties than the hydrophobic MD membranes. In addition, the hydrophilic membranes in PV do not favor the permeation of volatile organic compounds and thus the permeate water will be free of organics. This is especially attractive if the feed water contains a small amount of volatile organic compounds

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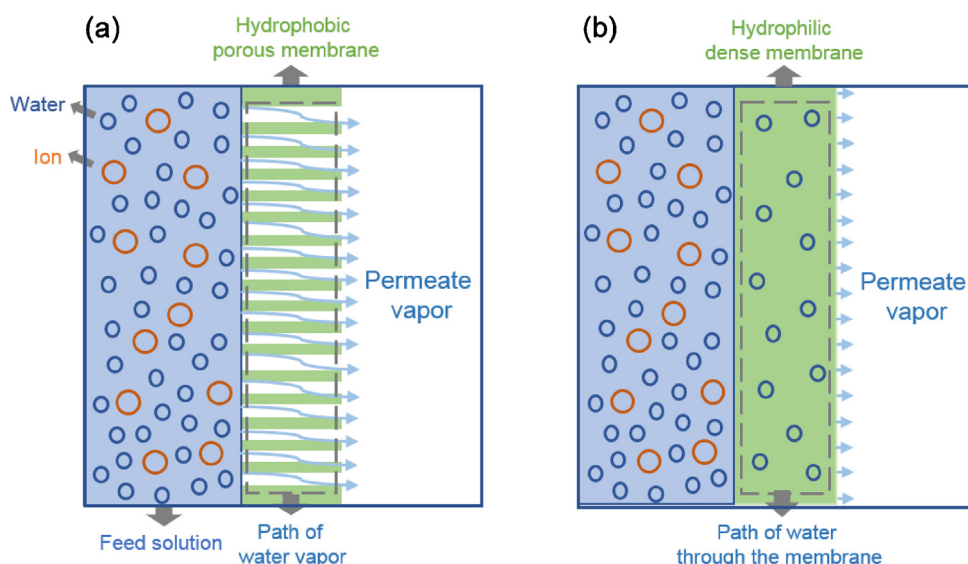
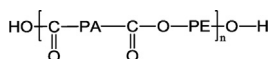


Fig. 1 – Schematic illustration of (a) membrane distillation with a porous membrane, and (b) pervaporation with a hydrophilic dense membrane.

which can hardly be removed by MD. It is commonly considered that PV is more competitive than MD when low-grade heat sources (e.g., solar energy, geothermal energy or waste heat) are available to heat the feed to an operating temperature in the range of 40–75 °C (Korin et al., 1996; Korngold et al., 1996), though both involve a liquid to vapor phase change. Neither PV nor MD is extensively used in desalination, and a main disadvantage with PV is the low flux as compared to MD. However, when the membrane has a high affinity and suitable molecular structure for water transport, the permeation flux through PV can be higher than that of MD (Korin et al., 1996; Korngold et al., 1996). Thus, PV is a strong contender for desalination, and developing hydrophilic membranes with a high flux is important for practical applications of pervaporative desalination.

Because of the advantageous characteristics of pervaporative desalination, a number of studies on PV for desalination have been carried out recently. The membranes used in pervaporative desalination include polymeric, inorganic and composites. The inorganic PV membranes are mainly based on zeolite (Zhou et al., 2016) and silica (Elma et al., 2015), while there are a variety of polymeric membranes including poly(vinyl alcohol) (Liang et al., 2018; Zhang et al., 2017; Zhang et al., 2018), cellulose acetate (Elewa et al., 2016), polyester (Sule et al., 2013), polyether ester (Quiñones-Bolaños et al., 2005), polyetheramide (Zwijnenberg et al., 2005), and polyethylene-based ion exchange membranes (Korin et al., 1996; Korngold et al., 1996). Recently, a new class of hydrophilic 2D inorganic material (e.g., MXene) (Liu et al., 2018) has also been employed for pervaporative desalination. In the present study, a hydrophilic poly(ether-block-amide) (PEBA) copolymer was used as the membrane material. PEBA is a group of thermoplastic elastomers with the general chemical structure as follows (Faruque and Lacabanne, 1987):



where PA is an aliphatic polyamide “hard” block based on nylon 6 [PA6] or nylon 12 [PA12], and PE is a polyether “soft” block based on poly(ethylene oxide) [PEO] or poly(tetramethylene oxide) [PTMEO] (Bondar et al., 1999). The hard PA blocks provide mechanical strength to the membrane, and the soft PE blocks yield high permeability due to the flexibility of the ether linkages (Bondar et al., 1999). PEBA copolymer used in this work is composed of 55 wt% of PEO and 45 wt% of PA12, and this specific grade of copolymer exhibits better hydrophilicity than the PEBA copolymer containing PTMEO blocks (Jonquière et al., 2002). As a specialty polymer, it shows a high water/moisture transmission rate (VTR) (Nguyen et al., 2001) and appears to be a promising material for gas dehydration (Potreck et al., 2009; Sabzi et al., 2014). However, very little work is done on this PEBA for pervaporation applications, especially

for pervaporative desalination of water. In this study, we exploited its high hydrophilicity and permeability for potential uses as membranes in desalination of high salinity water (1–20 wt%) by pervaporation.

Homogeneous membranes were prepared using the solution-casting method, and the membrane morphology was characterized. The separation performance was evaluated for pervaporative desalination of aqueous solutions at high salinities (up to 20 wt%) using NaCl, MgCl₂ and Na₂SO₄ as model solutes. The effects of feed salt concentration, operating temperature and membrane thickness on the desalination performance were studied. A batch process where the permeate stream was removed and collected continuously was also carried out to investigate the concentration polarization of the feed solution and membrane fouling during the course of pervaporative desalination. Batch process is suitable for the treatment of feed solution where varying quantities of feed water with different salt concentrations are encountered.

2. Experimental

2.1. Membrane preparation and characterization

The PEBA copolymer was generously supplied by Specialty Polymers, Arkema Inc. (Philadelphia, PA). In order to better understand the mass transport in the membrane, homogeneous membranes with well-defined thicknesses were used. They were prepared using the solution-casting method (Siemann, 2005), which involved three major steps: formulating the polymer solution, casting the polymer solution into films, and drying the cast solution to produce the final membranes. A predetermined amount of PEBA was dissolved in N-methyl-2-pyrrolidone (NMP) (Acros Organic Inc.) at 100 °C with vigorous stirring for 24 h to form a homogeneous solution with a PEBA concentration of 18 wt%, followed by standing still in an oven at 100 °C for 12 h to degas any entrapped air bubbles in the solution. The hot polymer solution was then cast onto a preheated glass plate (90 °C) positioned horizontally using a membrane casting assembly. The membrane casting was done quickly at ambient condition to ensure the polymer solution was evenly dispersed on the glass plate before it was cooled down, and the cast film was allowed to dry in an oven at 90 °C for 12 h to evaporate the solvent. The film was peeled off from the glass plate by immersing it into deionized water for 5 min. After the membranes were dried in an oven at 50 °C for 24 h,

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