Journal of Membrane Science 504 (2016) 75–88

Contents lists available at ScienceDirect

Journal of Membrane Science

journal homepage: www.elsevier.com/locate/memsci

Fabrication and characterization of fabric-reinforced pressure retarded osmosis membranes for osmotic power harvesting

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ARTICLE INFO

Article history:
Received 8 September 2015
Received in revised form
29 December 2015
Accepted 3 January 2016
Available online 12 January 2016

Keywords:
Pressure retarded osmosis (PRO)
Fabric-reinforced membrane
Tricot fabric
Membrane deformation
Stretching
Osmotic power

ABSTRACT

In recent years, pressure retarded osmosis (PRO) has attracted increasing interest in the harvesting of the renewable osmotic power. However, its performance can be significantly influenced by the membrane deformation in the operation when the PRO membrane is lack of sufficient mechanical strength. In this study, we fabricated three different fabric-reinforced thin-film composite (TFC) flat-sheet PRO membranes for osmotic power harvesting. These membranes were prepared through integrating three different types of fabric reinforcement (i.e., tricot fabric, woven fabric and nonwoven fabric) in the membrane substrate layer. It was found that the fabric reinforcement plays an important role in the membrane structural property and mechanical property, both of which can significantly influence the PRO performance. The nonwoven-fabric-reinforced membrane had the greatest structural parameter and thus exhibited the lowest performance. Although the tricot-fabric-reinforced membrane and the woven-fabric-reinforced membrane had similar performance in the forward osmosis (FO) condition ($\Delta P=0$), the former showed superior performance in the PRO condition ($\Delta P>0$). This is mainly because the tricot-fabric-reinforced membrane had better mechanical resistance to the multi-directional tensile stretching, which rendered it less prone to changes in structural and separation properties in the PRO operation. This further suggests that the tricot fabric has high potential for future PRO membrane fabrication. The current study also elaborates the coupled effects of compression and stretching on PRO membrane deformation and performance. The results obtained in this study may provide important insights into reinforced PRO membrane design.

1. Introduction

Pressure retarded osmosis (PRO) is one of the most promising technologies for harvesting the renewable osmotic power from the mixing of two solutions with different salinities [1–5]. In PRO, water in a low salinity feed solution (FS) permeates through a selective membrane into a high salinity draw solution (DS) where a hydraulic pressure lower than the osmotic pressure difference across the membrane is applied [6]. In this controlled mixing process, the osmotic power can be eventually harvested in terms of electricity by running the pressurized DS through a hydroturbine.

Although PRO has been proposed for around 40 years [7], its development was retarded primarily due to the lack of suitable PRO membranes from the technical point of view. Early studies revealed that the membranes used for PRO could suffer severe internal concentration polarization (ICP) within the support layer and thus delivered extremely low performance [8–12]. While the ICP can be reduced by tailoring the membrane support layer [13–17], recent studies found that membrane deformation in the operation can also significantly reduce the PRO performance [18–20]. Membrane deformation gives rise to a substantially increased reverse solute diffusion (RSD, i.e., solute leakage from DS into FS) that can further enhance ICP [18,19]. As such, the mechanical strength has been generally regarded as one of the critical criteria for PRO membranes [18–23]. Recently, it was reported that robust

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http://dx.doi.org/10.1016/j.memsci.2016.01.004
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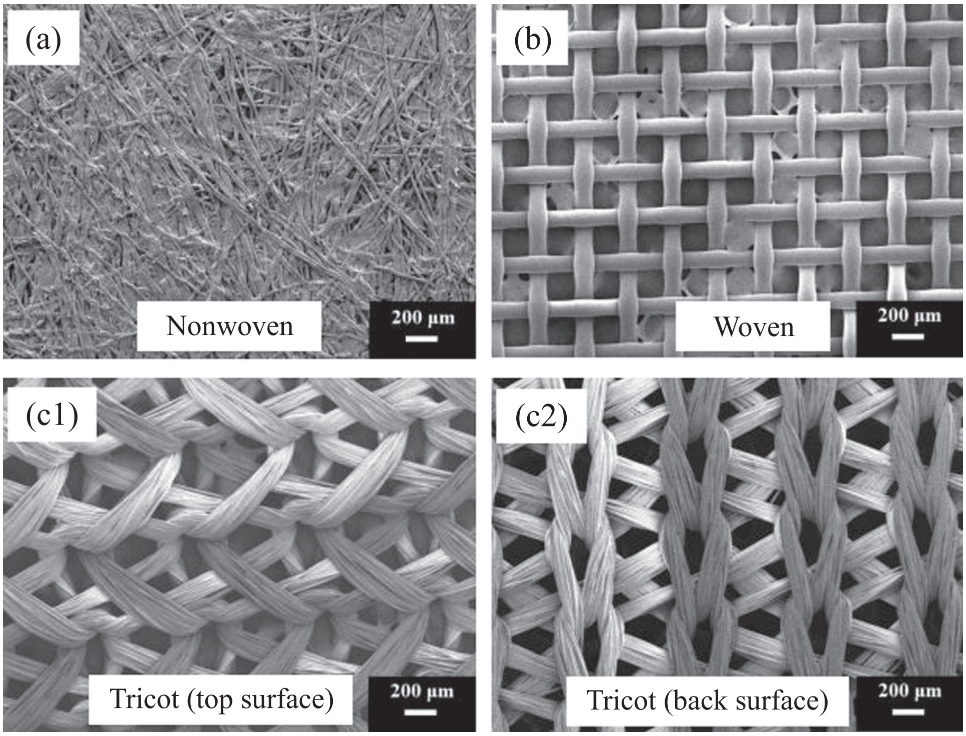

Fig. 1. SEM images of (a) non-woven fabric, (b) woven fabric, and (c) tricot fabric (c1 is top surface and c2 is back surface).

hollow-fiber membranes can be fabricated for PRO with appreciable power density [24–26]. The improved mechanical strength of those hollow-fiber membranes was achieved by using new types of materials as well as optimizing the substrate structure and/or hollow-fiber dimension [24–26].

In the context of flat-sheet membrane, the mechanical strength can be significantly reinforced by integrating a suitable fabric in the support layer in addition to using above-mentioned strategies for reinforcing hollow-fiber membrane. For example, commercial RO membranes are typically reinforced with a nonwoven fabric at the back of substrate layer. However, a fabric reinforcement integrated in the support layer could result in an increased membrane structural parameter [14] and thereby an increased ICP effect in the PRO process. Thus, many flat-sheet PRO membranes reported in the literature only consisted of a polymeric substrate layer and a rejection layer without using a fabric reinforcement [27–30]. This, in turn, could result in a remarkably reduced membrane mechanical strength [23], which is likely to reduce the PRO performance and limit the large-scale membrane production. Although some membranes integrated a nonwoven fabric or a woven fabric in the support layer [18,22,23,31], relatively low PRO performance was obtained in the testing. Therefore, it is necessary to select new types of fabric for PRO membrane fabrication and further study the effect of fabric on the PRO membrane performance.

In the PRO operation, She et al. revealed that the membrane mechanical stability of a flat-sheet membrane is not only influenced by the membrane intrinsic mechanical strength but also strongly dependent on the spacer geometry in the feed flow channel [19]. A feed spacer with greater opening size could result in more severe membrane deformation and thus lower PRO performance [19]. Therefore, many studies selected the feed spacer with very small openings to sufficiently support the membranes against tensile deformation in the PRO testing (e.g., using fine mesh [27–29,32] or RO permeate carrier [19,30,33]). However, using this type of spacer could result in several adverse effects: (1) increase feed flow resistance due to confined space in the feed channel [19,34]; (2) reduce effective membrane filtration area due to “shadow effect” [19,20]; (3) potentially exacerbate external fouling on membrane surface due to accumulation of foulants within the voids of the spacer [35–37]. Therefore, it should be more practical to use a typical net-type feed spacer (as the one used in RO/NF/UF spiral wound modules) in the PRO testing. In addition, there is an urgent need to develop stronger PRO membranes that can use typical net-type spacers in the PRO process without loss of membrane mechanical stability.

The objectives of this study are to (1) fabricate and characterize fabric-reinforced TFC PRO membranes for osmotic power harvesting, and (2) explore the underlying mechanisms on PRO membrane deformation and performance when using a typical net-type feed spacer in the testing. For the first time, tricot fabric, which allows isotropic transfer of multi-directional tensile forces, is selected to reinforce the PRO membrane in this study. Woven fabric and nonwoven fabric are also selected for comparison. The implications for reinforced-PRO membrane design are elaborated.

2. Materials and methods

2.1. Chemicals and materials

Unless otherwise specified, all chemicals used in current study were ACS grade. Polysulfone beads (PSf, molecular weight 75,000–81,000 Da, Solvay Advanced Polymers, LLC, GA) were used for casting membrane substrates. N-methyl-2-pyrrolidone (NMP, Merck Schuchardt OHG, Hohenbrunn) was used as the solvent for preparing casting solution. Polyvinyl pyrrolidone (PVP, average molecular weight 1,300,000 Da, Alfa Aesar, MA) were used as pore former in the casting solution. Chemicals used for interfacial polymerization included m-phenylenediamine (MPD, Sigma-Aldrich Pte. Ltd, Singapore), trimesoyl chloride (TMC, Sigma-Aldrich), and n-hexane (Merck). Sodium chloride (NaCl, Merck, PH EUR) was dissolved in ultrapure water to prepare both draw solutions and feed solutions. The Ultrapure water with a resistivity of