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Novel crossflow membrane cell with asymmetric channels: Design and pressure-retarded osmosis performance test

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ABSTRACT

Pressure-retarded osmosis (PRO) has the potential to convert salinity gradient energy to hydraulic energy via a semi-permeable membrane. The performance of an osmotic membrane is usually evaluated using a crossflow membrane test cell with symmetric channels. However, it is not possible to test a PRO membrane under conditions of large differences in hydraulic pressure because the membrane cannot be supported in the channel inlet and outlet with a cavity. In this study, we present a newly designed PRO crossflow test cell that features asymmetric channels on both sides of the membrane. This asymmetric design prevents membrane bulge and rupture in the channel inlet and outlet even at an applied hydraulic pressure difference greater than 54.5 bar. Excellent performance of this novel PRO cell was demonstrated using two different membranes at various operating pressures. To prevent membrane deformation at open spaces between spacer strands, a feed channel spacer should be selected carefully. Accordingly, the effects of tricot feed spacers with different voidages and thicknesses on PRO performance were also investigated.

1. Introduction

Seawater is an attractive energy resource if it can be used together with river water to exploit the salinity gradient in a mixing process via a semi-permeable membrane. Salinity-gradient energy that can be converted into electrical energy has the potential to become a sustainable energy source in the near future [1–3]. Such salinity-gradient power is completely renewable and sustainable because of the earth's continuous hydrological cycle [4,5]. In particular, unlike solar and wind power, which are characterized by periodicity, such osmotic power is non-periodic [6]. This is one reason that osmotic power has drawn considerable attention as a potential renewable energy source.

Pressure-retarded osmosis (PRO) is one of the salinity-gradient power generation technologies [7–11]. The principle of PRO is to use the free energy of mixing that is released when fresh river water flows into the sea. PRO uses a semi-permeable membrane as a means of mixing and requires a hydraulic pressure difference less than the osmotic pressure difference for energy conversion. In PRO, water permeates through a semi-permeable membrane against a hydraulic pressure gradient because of the osmosis phenomenon. That is, PRO converts the salinity gradient (chemical) energy between fresh water and seawater into hydraulic (kinetic) energy via the semi-permeable membrane. For additional energy conversion, a hydroturbine is then used to convert the hydraulic (kinetic) energy to electrical energy.

A membrane power density of 5 W/m^2 has been presumed to make a PRO osmotic power plant commercially viable [12,13]. To date, no commercial membrane has demonstrated this target power density using fresh river water and seawater. Accordingly, most recent PRO studies have focused on the development of high-performance PRO membranes. Some research teams have recently reported the development of flat-sheet and hollow-fiber thin-film composite (TFC) PRO membranes with sufficiently high power density ($>5\ W/m^2$) on a laboratory experiment scale [14–17]. The distinct feature of these PRO membranes is that their support layers are designed to be thin, hydrophilic, and highly porous to allow large quantities of water flux. Additionally, a key feature of such PRO membranes is the ability to withstand the high hydraulic pressure that is necessary for the PRO process.

Membrane performance and characteristics are usually evaluated using a crossflow membrane test cell. Performance tests of PRO membranes developed for osmotic power generation have also been conducted in crossflow cells that differ slightly from conventional crossflow cells used for forward osmosis (FO) membranes [14,16–27]. The feed channel geometry of a conventional crossflow

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cell was modified to avoid severe membrane stretching and bulging at the inlet and outlet regions of the feed channel due to the high applied pressure. This membrane deformation can significantly influence PRO performance. However, such a modified crossflow cell was not able to prevent membrane damage under conditions of large differences in hydraulic pressure. For this reason, the test pressure was severely restricted. Thus, to date, accurate performance tests of PRO membranes have been hindered by the absence of an adequate crossflow test cell for PRO membranes.

In previous studies, several PRO-cell modifications have been implemented to prevent membrane deformation [14,16–24]. For example, recently developed crossflow PRO membrane cells had a porous stainless-steel mesh plate between two channels or parallel slit openings in the inlet and outlet of the feed channel to reduce membrane deformation as much as possible [16,22,24,28]. The porous stainless-steel plate inserted in a PRO cell provided good support for the membrane but obstructed the feed flow, resulting in a considerable pressure drop in the feed channel. Additionally, the pressure drop caused by the feed channel spacer was not able to be measured due to the use of the porous stainless-steel plate [16,22,24]. The other PRO cell with parallel slit openings in the feed channel inlet and outlet required the edges of the test membrane coupon to be covered with water-resistant tape, because the cell design with parallel slit openings was insufficient to prevent membrane strain at high hydraulic pressures [28]. Thus, the major limitation of the crossflow PRO cells is their inability to prevent membrane tension under conditions of large differences in hydraulic pressure.

If a net-type spacer is used in the feed channel for PRO experiment, the membrane is deformed and bulged in the open spaces between spacer strands under PRO testing conditions [20]. The deformed membrane between spacer strands under high pressure can alter the feed channel geometry and consequently change the flow conditions of the feed solution fluid. Thus, such a typical net-type spacer is insufficient to support the membrane under conditions of large differences in hydraulic pressure. That is, the pressurized draw solution flow influences the feed solution flow unless tricot spacers are used. Eventually, a major role of the tricot fabric spacer is to maintain the feed channel geometry under high pressure [29–31]. Accordingly, in the PRO test cell, the feed channel space between the membrane and feed channel wall must be fully filled with several sheets of tricot fabric spacer for membrane protection under high-pressure operation.

In this study, we present a newly designed crossflow membrane test cell with asymmetric channels on both sides of the membrane. The design and operation of the crossflow membrane test cell are detailed below. Experiments using two different membranes under conditions of large differences in hydraulic pressure demonstrated that the performance of the newly developed crossflow PRO cell was excellent. FO and RO experiments were also conducted on the PRO test cell to assess membrane transport properties. Finally, the effects of voidage and thickness of the tricot feed spacer on PRO performance were investigated.

2. Experimental

2.1. Membranes and spacers

To determine the integrity of the newly developed crossflow PRO cell, two different membranes were used. The first was a TFC polyamide (PA) PRO membrane from Toray Chemical (Japan, Woongjin Chemical, as was; Fig. 1) and the second was a cellulose-based FO

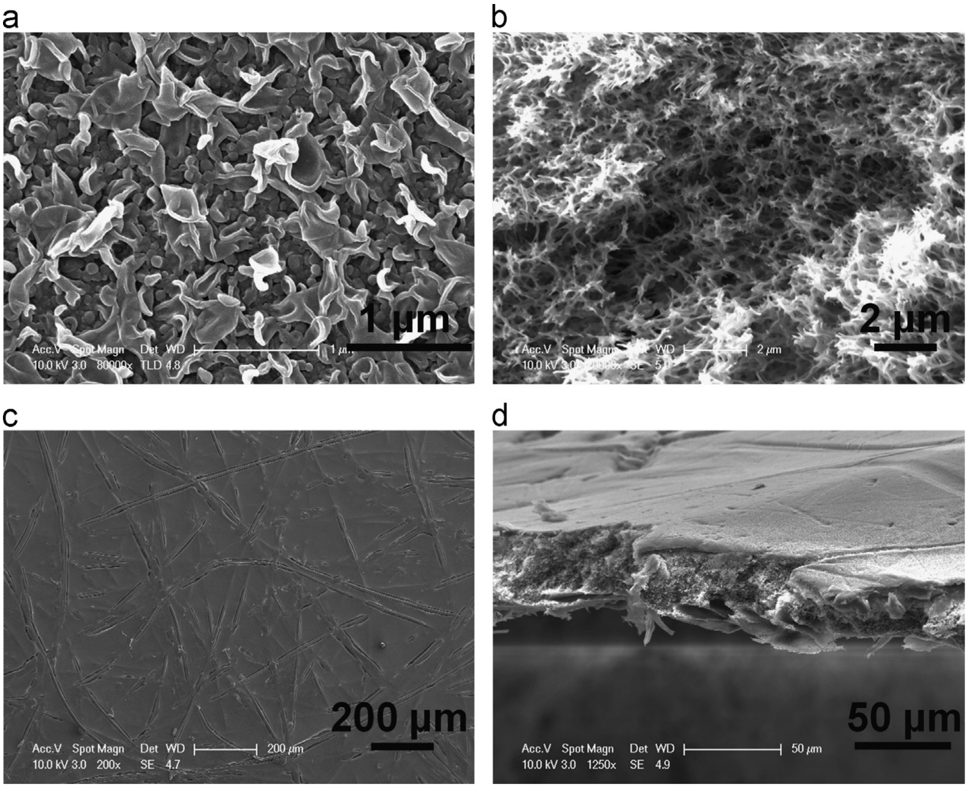

Fig. 1. SEM micrographs of a TFC-PRO membrane with sponge-like structure. (a) active layer surface, (b) support layer cross section, (c) PET fabric layer surface, and (d) support layer cross section with PET fabric layer removed. The TFC PRO membrane used for this PRO study had a highly porous support layer, consisting of a fully sponge-like structure suitable for high-pressure operation. The TFC PRO membrane was measured to be 160 μm thick. The sponge-like structure is well known to be morphologically and mechanically superior to the finger-like macrovoid structure.