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A thin-film composite-hollow fiber forward osmosis membrane with a polyketone hollow fiber membrane as a support

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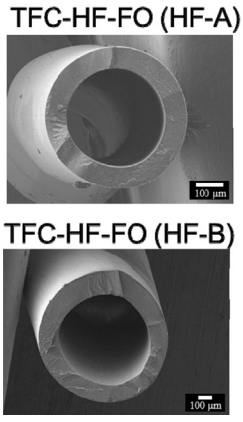
HIGHLIGHT

- Preparation of HF membranes by using porous polyketone HF supports having different diameters.
- By using the FO-fitting method for estimation of the intrinsic membrane parameters.
- Our fabricated HF membranes with smaller diameter showed one of the highest FO performances.

GRAPHICAL ABSTRACT



Samples	Inner diameter [μm]	Outer diameter [μm]	Thickness [μm]
HF-A	347	480	66.5
HF-B	609	893	142

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ABSTRACT

We have developed a thin-film composite (TFC) hollow fiber (HF) forward osmosis (FO) membrane using a polyketone HF membrane as a support. To investigate the effect of the diameter of the HF support membrane on the resulting FO performance of the TFC-HF-FO membrane, two-types of HFs with different inner diameters (HF-A: 347 μm and HF-B: 609 μm) were used. The FO performance of the prepared TFC membranes was measured and then analyzed using intrinsic membrane parameters obtained by an FO fitting method. These intrinsic parameters can be used to estimate the experimental data under various operating conditions. The prepared TFC-FO membrane using the HF with smaller diameter (TFC-FO (HF-A)) showed higher FO flux and better mechanical properties than those of the membrane prepared using the HF with larger diameter (TFC-FO (HF-B)), while higher operational pumping energy consumption is necessary because of higher bore-side pressure drop. Barlow's equation and the Hagen-Poiseuille equation were used to analyze the experimental data on the maximum burst pressure and the data on bore-side pressure drop of the prepared TFC FO membranes, respectively. The prepared TFC-FO membrane using the HF with smaller diameter showed one of highest FO fluxes yet reported in the literature.

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1. Introduction

Recently, forward osmosis (FO) has attracted much interest because of its promising potential in water- and energy-related applications, such as desalination [1–4], wastewater treatment [5–7], product enrichment [8], and power production from salinity gradient [9,10]. FO is based on natural water transfer from a low concentration side (feed solution: FS) to a high concentration side (draw solution: DS) through a semipermeable membrane. To apply FO technology to the above-mentioned applications, improvements in both FO-membrane and DS technology are required [11].

In the case of the FO membrane, one of the main problems is lower water flux due to the existence of internal concentration polarization (ICP) generated in the porous support layer [12,13]. To decrease ICP in the support layer, much research has been carried out with the intent of tuning support layer structure [14–16] and increasing hydrophilicity [17] by changing the support layer preparation condition, selecting the types of polymer material, and chemically pre- or post-modifying the support layer. Up to now, various types of polymer materials, such as polysulfone [18], polyether sulfone [19], sulfonated polysulfone [20], polyphenylsulfone [20], cellulose acetate [21], cellulose triacetate [21], cellulose acetate butyrate [21], hydrophilic cellulose acetate propionate [22], sulfonated polyether ketone [23], polyacrylonitrile [24], polybenzimidazole [25], polyamide-imide [26], and polyketone [27], were used in the support layer in order to improve the FO flux performance [25,27], hydraulic pressure resistance [25], and chemical resistance [27] of the prepared FO membrane. Although FO-membrane developments are still required in respective target applications, recent progress has already achieved several times higher FO flux than that of the first commercialized cellulose-based FO membrane from Hydration Technology Innovation (HTI) [28]. The recent developments in FO-membrane technology have provided an opportunity to use the FO process in industry.

On the other hand, to demonstrate the advantage of FO in industrial use, a module installation is needed for pilot-scale performance estimation. Spiral-wound, plate-and-frame, and hollow-fiber (HF) element configurations have been proposed as possible module elements in FO. A spiral-wound FO module is often used because most commercialized FO membranes are based on a flat-sheet type membrane. However, an HF-type FO membrane has advantageous features, such as large specific membrane area, high packing density, and appropriate flow pattern [29].

In our previous study [27], we developed a flat-sheet type, thin-film composite (TFC), FO membrane using a highly porous polyketone microfiltration membrane as a novel support. The prepared FO membrane showed one of highest FO performances in the literature because of the high porosity of the support and preferable attachment between active and support layers. In this study, making use of the advantageous features of the HF-type FO membrane as mentioned above, we have developed a TFC-HF-FO membrane using an HF support prepared with polyketone material. To understand the dimensional design of the HF FO membrane, two-types of HF supports having different diameters were used.

2. Experimental

2.1. Materials and chemicals

Two types of polyketone HF membranes (HF-A and HF-B) were kindly provided by ASAHIKASEI FIBERS Co., Japan, and were used as support membranes for the preparation of TFC-HF-FO membranes. The polyketone HF support membranes were prepared *via* the non-solvent induced phase separation (NIPS) method described in our previous report [27]. For preparation of the active layer, we used 1,3,5-benzenetricarbonyl trichloride (TMC), (±)10-camphorsulfonicacid (CSA), hexamethylphosphoric triamide (HMPA), 1,3-phenylenediamine (MPD), sodium dodecyl sulfate (SDS), and triethylamine. The first three chemicals were obtained from TOKYOKASEI Co., Tokyo, Japan, and the last three, from Wako Pure Chemical Co., Osaka, Japan. Galwick® (Porous Materials Inc., New York, USA) was used in liquid-liquid porometer experiments. For the FO performance tests, sodium chloride (Wako Pure Chemical Ltd., Osaka, Japan) solutions were prepared and used as draw solutions. All chemicals used in this study were of analytical grade and used without further purification. Ultra-pure water was supplied by a Milli-Q ultra-pure water system (Millipore, Bedford, MA, USA).

2.2. Characterization of the HF support membrane

2.2.1. Liquid-liquid porometer (LLP) measurements

The pore size and distribution of the polyketone HF support membranes were characterized with a liquid-liquid porometer (LLP) (LLP-1200 Porous Material Inc., USA) [30]. The LLP can evaluate the open pore diameter (active for flux) at the bottleneck portion with lower hydraulic pressure than that used in the conventional bubble-point method. In the LLP measurement, the HF membrane was soaked in a wetting liquid that is subsequently pushed out by another immiscible liquid when the applied pressure increases. The experimental procedure allows correlating the applied pressure and the corresponding pore diameter. Here, we used 2-propanol as the wetting liquid and Galwick® as the immiscible liquid. The pore diameter D_{pore} was then calculated using the following equation [31]:

$$D_{pore} = 4\gamma_1 \cos\theta_1 / \Delta p_{app} \quad (1)$$

where D_{pore} is the opened (active for flow) pore diameter at the bottleneck part, γ_1 is interfacial tension between the two liquids, θ_1 is the contact angle between the wetting liquid and the membrane surface, and Δp_{app} is the applied pressure for the displacement of the wetting liquid. The contact angle, θ_1, between the liquid and membrane material interface was assumed to be zero because $\gamma_{L1/L2}$ was very small (4–9 dyne/cm), indicating completely wetting state ($\cos\theta_1 = 1$) as shown in the supporting information (Fig. S2) [31].

2.2.2. Porosity measurement of the HF support membranes

The porosity of the HF support membranes (HF-A and HF-B) were obtained by measuring the volumetric weight. The weights of 5 cm-long pieces of the HFs were precisely measured with an electronic

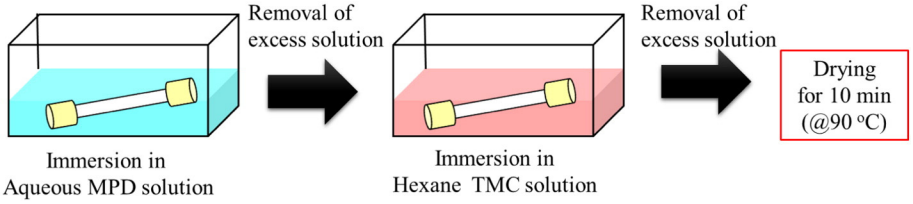

Fig. 1. Procedure for the interfacial polymerization of the shell side of the hollow fiber membrane support.