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# Experimental and simulation studies of two types of 5-inch scale hollow fiber membrane modules for pressure-retarded osmosis

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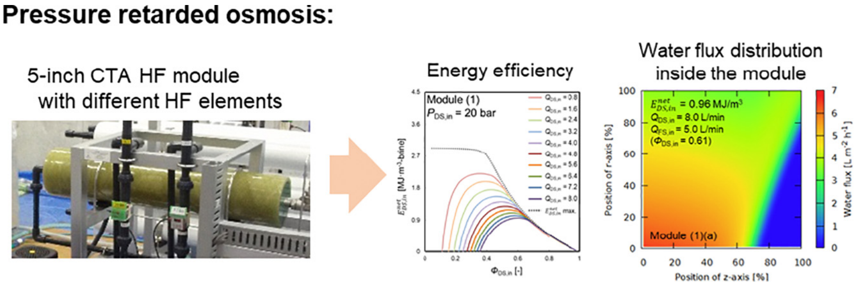
## GRAPHICAL ABSTRACT



## ARTICLE INFO

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## ABSTRACT

This study experimentally and theoretically analyzed the performance of two types of large-scale hollow fiber (HF) forward osmosis (FO) modules for pressure retarded osmosis (PRO). The effects of operating conditions on the module performance of the 5-inch scale HF modules with a cross-wound HF configuration were investigated. A modified analytical model, based on the friction-concentration polarization (FCP) model, which combined the PRO theory with water flux and salt leakage, was proposed for PRO performance estimation. The theoretical results agreed within 9.7% deviation with the experimental results under all conditions. The energy efficiency of the HF PRO module was also theoretically derived. The power generation estimation for the 5-inch membrane module revealed that 10 to 15% of the energy could be recovered from the reverse osmosis seawater desalination process. However, some parts of the membrane could not be used efficiently inside the modules because of the non-optimal dimensions. Therefore, new types of modules, having shorter lengths and larger module diameters, were proposed and provided greater net energy output, as compared with the original module, due to the reduction of both the region where the water was not sufficiently permeated and the pressure drop inside the HF membrane.

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## 1. Introduction

Reverse osmosis (RO) is widely used as a seawater desalination technique due to its lower energy cost than the previously conventional evaporation method, owing to the absence of latent heat energy. In recent years, the energy consumption has been further reduced by including a pressure exchanger that enables the recovery of the pumping energy from RO desalination [1]. Recent RO developments have achieved a low energy consumption of approximately 2.5 $\mathrm{kWh{\cdot}m^{-3}}$ for water production [2,3], approaching the theoretical minimum value of approximately 1.0 $\mathrm{kWh{\cdot}m^{-3}}$ [4]. However, further reduction of the energy consumption is still required, due to the growing demand for secure water resources. In addition, the large amount of concentrated brine, an RO desalination plant by-product, that is disposed into the surrounding environment should also be considered [5,6].

Accordingly, pressure retarded osmosis (PRO) has attracted attention as an emerging technology to solve these problems [5,7–9]. PRO enables the conversion of the salinity gradient energy into electric energy by using a semipermeable membrane [10–13]. When a PRO system is combined with a modern RO desalination plant, approximately 3.87 $\mathrm{MJ{\cdot}m^{-3}}$ of energy can potentially be generated due to the Gibbs free energy of mixing between the RO brine (with an assumed concentration of 1.2 $\mathrm{mol\,L^{-1}}$) and another low-salinity water, such as wastewater or treated sewage (with an assumed concentration of 10 $\mathrm{mmol\,L^{-1}}$) [14]. In addition, since the PRO process also enables the dilution of the concentrated seawater, the environmental impact of the disposed RO brine can be sufficiently reduced [15].

Recently, in order to investigate and improve the performance of PRO, many studies have been conducted at a lab scale [16–23]. However, to estimate the feasibility, especially of a PRO pilot plant, a pilot scale experimental study using the membrane module is required in addition to the lab scale experiment because the PRO performance at the pilot scale is highly influenced by not only the PRO membrane performance, which is considerable at the lab scale, but also the operating conditions, module characteristics, and module dimensions. To date, although there have been a few pilot scale studies of PRO process performance [24–26], further experimental investigation of the PRO process on a pilot scale is still required. Moreover, accurate models for estimating the performance of PRO modules at the pilot scale are still lacking, and, therefore, optimized module-specific models should be developed. Thus, both experimental and theoretical studies using pilot scale PRO membrane modules are required for estimating, designing, and improving pilot scale PRO systems.

Recently, several types of module configurations, such as hollow fiber (HF) [24], spiral wound [25,26], and plate and frame [27] configurations have been proposed for pilot scale PRO membrane modules. Among them, the HF module has been proposed as an interesting element configuration because of its high packing density and the appropriate flow patterns in the module [24,28]. In addition, current HF RO modules can be directly used as PRO modules because they have 4 ports, including an inner HF bore side inlet and outer HF shell side outlet ports, without additional modification required for the spiral wound membrane module [28].

In our previous study, we experimentally and theoretically investigated osmotically driven module performance using a 5-inch scale HF membrane module under forward osmosis (FO) operation [28]. A simple integral calculation model, developed from the friction concentration polarization (FCP) model, was proposed in order to theoretically explain and predict the HF module performance under FO operation. Although our developed model agreed well with the experimental data for an HF module under a wide range of FO operating conditions, its versatility is still unclear, especially for different HF modules under PRO operation.

In this study, we experimentally and theoretically investigated the pilot scale performance of two types of HF modules under a wide range of PRO operating conditions. To improve the accuracy of the calculations, we also modified the FCP model by combining the PRO theory for water flux and salt leakage with our previous model [28]. Furthermore, the energy efficiency of the HF PRO module was theoretically obtained by comparing its performance with the Gibbs free energy of mixing under different operating conditions.

## 2. Theory

### 2.1. Modified FCP model for PRO

The friction concentration polarization (FCP) model [29] is an initial analytical model of an HF RO module in which the pressure loss inside the HF is considered based on the Kimura-Sourirajan membrane transport equation [30]. The FCP model is based on the stepwise segmental (integral) calculation of both the inner bore and outer shell sides of the HF membrane, considering the external concentration polarization, pressure drops, and concentration profiles in the RO module. In our previous study [28], we combined FO theory with an FCP model in order to estimate the HF module performance under FO operation. Herein, to apply this modified FCP model for PRO operation, we have improved the model by combining PRO theory with the FCP model.

Osmotically driven water flux is often expressed using the intrinsic parameters of the membrane, such as the water permeability coefficient, $A$ $[\mathrm{L{\cdot}m^{-2}{\cdot}h^{-1}{\cdot}bar^{-1}}]$, solute permeability coefficient, $B$ $[\mathrm{L{\cdot}m^{-2}{\cdot}h^{-1}}]$, and structural parameter, $S$ [μm]. In the case of PRO operation, the water flux, $J_w$ $[\mathrm{L{\cdot}m^{-2}{\cdot}h^{-1}}]$, can be expressed by considering the membrane orientation and the internal and external concentration polarization effects, based on the solution diffusion model, as follows [17]:

$$J_w = A\cdot\left\{\frac{\pi_{DS,b}\exp\left(-\frac{J_w}{k}\right) - \pi_{FS,b}\exp\left(\frac{J_w S}{D_{diff}}\right)}{1 + \frac{B}{J_w}\left[\exp\left(\frac{J_w S}{D_{diff}}\right) - \exp\left(-\frac{J_w}{k}\right)\right]} - \Delta P_{DS-FS}\right\} \tag{1}$$

where $\pi_{\mathrm{DS,b}}$ [bar] and $\pi_{\mathrm{FS,b}}$ [bar] are the osmotic pressures in the bulks of the more concentrated (draw solution: DS) and less concentrated solutions (feed solution: FS), respectively; $\Delta P_{\mathrm{DS-FS}}$ [bar] denotes the hydraulic pressure difference between the shell side DS and the bore side FS of the HF membrane; and $D_{diff}$ $[\mathrm{\mu L{\cdot}m^{-1}{\cdot}h^{-1}}]$ and $k$ $[\mathrm{L{\cdot}m^{-2}{\cdot}h^{-1}}]$ are the diffusivity and mass transfer coefficient, respectively, of the draw solute.

The reverse solute flux ($J_s$ $[\mathrm{mol{\cdot}m^{-2}{\cdot}h^{-1}}]$) from the DS to FS can be expressed as follows [31]:

$$J_s = \frac{J_w + A\Delta P_{DS-FS}}{\frac{A}{B}\cdot\nu RT} \tag{2}$$

where $\nu$ [−], $R$ $[\mathrm{bar{\cdot}L{\cdot}mol^{-1}{\cdot}K^{-1}}]$, and $T$ [K] are the van't Hoff factor, gas constant, and solution temperature, respectively.

In the FCP model, the pressure drop at the shell side of the HF (DS side) is expressed by the Ergun equation as follows [29,32]:

$$\frac{dP_{shell}}{dr} = \frac{150(1-\epsilon)^2}{\epsilon^3}\cdot\frac{\mu_{shell}u_{shell}}{(1.5d_{shell})^2} + \frac{1.75(1-\epsilon)}{\epsilon^3}\cdot\frac{\rho_{shell}u_{shell}^2}{1.5d_{shell}} \tag{3}$$

where $\varepsilon$ [−] is the porosity of the HF module; $\mu_{\mathrm{shell}}$ [Pa·s], $u_{\mathrm{shell}}$ $[\mathrm{m{\cdot}s^{-1}}]$, and $\rho_{\mathrm{shell}}$ $[\mathrm{kg{\cdot}m^{-3}}]$ are the viscosity, flow rate, and density of the outer shell side solution of the HF membrane, respectively; and $r$ [m] is the coordinate in the radial direction.

The pressure drop at the inner bore side of the HF membrane (FS side) is expressed by the Hagen-Poiseuille equation, as follows [28,29,32]:

$$\frac{dP_{bore}}{dz} = \frac{32\mu_{bore}u_{bore}}{d_{in}^2} \tag{4}$$

where $d_{\mathrm{in}}$ [m], $z$ [m], $\mu_{\mathrm{bore}}$ [Pa·s], and $u_{\mathrm{bore}}$ $[\mathrm{m{\cdot}s^{-1}}]$ are the inner diameter of the HF, axis coordinate, bore side solution viscosity, and bore