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Evaluation of an element-scale plate-type forward osmosis: Effect of structural parameters and operational conditions

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ABSTRACT

This is the first study investigating a plate-type forward osmosis (FO) element in two different operating modes: FO and pressure assisted FO (PAFO). A baseline test was conducted to assess the FO process under different structural parameters and operating conditions. For the PAFO, both the naturally occurring pressure and artificially applied hydraulic pressure in at the feed solution (FS) were considered. FO water flux increased with an increase in the temperature (from 20 to 30 °C) and the draw solution (DS) concentration (0.4 to 0.7 M). In addition, when the flow rate of the FS increased, the water flux increased and the inlet pressure at the FS side also increased. In the PAFO mode, the water flux increased with an increase in the hydraulic pressure, but the water flux decreased with a 1.5 bar hydraulic pressure. The increase in the water flux became smaller as the flow rate difference between the FS and DS increased, which is not the same as the FO mode. This may due to that as the flow rate increases, and the hydraulic pressure is further increased, the central portion of the membrane comes into contact with the spacer at the DS side (bowing phenomenon).

1. Introduction

Forward osmosis (FO) has received a significant amount of attention in recent years due to a wide range of potential applications [1,2], including brackish water or seawater desalination [3], wastewater treatment [4], food industry [5] and fertilizer dilution [6]. The FO process does not need an hydraulic pressure for water production due to its driving force is the osmotic pressure between the high concentration side called as draw solution (DS) and low concentration side called as feed solution (FS), separated by a membrane and resulting in the pure water passing through the semi-permeable membrane from FS to DS [7,8]. Compared to the pressure-driven membrane processes, the FO process has certain advantages including low or no operational pressure [9], thus there is less propensity for fouling and ease of cleaning [10]. However, the asymmetric structure of the FO membrane can result in a severe internal concentration polarization (ICP), which leads to a decrease in the driving force [11].

FO studies have been focused on the FS facing the active layer (FS-AL or FO mode) and DS facing the active layer (DS-AL or pressure retarded osmosis (PRO) mode) depending on the membrane orientation [12,13]. The water flux in the PRO mode was found to be higher than that in the FO mode. However, the PRO mode exhibited more fouling propensity than the FO mode the because foulants in the FS can be easily trapped inside the porous structure in the supporting layer (SL) of the membrane, which is not easily removed via physical cleaning [7]. However, several recent studies have been carried out with additional hydraulic pressure on the FS in the FO (usually referred to as pressure assisted FO, PAFO), which has two driving forces: osmotic pressure and external hydraulic pressure. PAFO has been reported to improve the performance of FO (e.g., water flux) and to overcome the disadvantages of FO (e.g., reverse salt flux, RSF) [1,4,14]. Lutchmiah et al. [15] increased the water flux by about 49% from 4.61 to 6.87 L/m^2/h (LMH) when the hydraulic pressure increased from 0 to 0.8 bar. A decrease in the RSF was also reported with an increase in the water flux when the pressure from 0 to 5 bar was applied [16].

Previous researches on FO optimization have been mostly carried out using a lab-scale membrane test cell loaded with a flat-sheet membrane. A flat-sheet FO membrane coupon was used in the lab-scale FO units, and the effective membrane area of the membrane coupon was relatively small, and the hydrodynamic conditions of the membrane test cell was quite simple. The lab-scale FO units (e.g., membrane test cells) may be suitable to investigate FO mechanisms rather than to study the design and its optimization. The full-scale membrane also exhibits quite different behavior compared to a lab-scale membrane test cell. Therefore, to avoid a design error, a pilot scale or an element scale experiment is essentially recommended when designing pilot-scale FO processes [17]. Thus, a better understanding of the behavior in a pilot scale FO or an element scale FO is needed for obtaining a more realistic

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perception for FO scale-up [18].

So far, however, there have some trials to test a large-scale FO module. Kim et al. conducted a detailed study linking the operating conditions (flow rates, inlet pressures) with the resulting performance (water flux, RSF, fouling and cleaning efficiency) of an 8″ spiral wound FO (SWFO) module, which provided important insights into the operability of current SWFO modules at a full scale [18]. This large scale SWFO module generally needs four ports of inlets and outlets: two ports of both inlets and outlets for each FS and DS, resulting in four ports for each solution. In the SWFO module, there is a feed channel that exists between the rolled membrane leaves, where the FS is being circulated. The DS flows further into the membrane envelop via central tube. Therefore, flow patterns and resistance within the flow stream of both FS and DS are different and subsequently they are affected by the specified module design. In addition, there is a dead zone in the SWFO modules because the flow path inside the DS channel of SWFO has a winding structure that forms in the edge of the draw flow path. As a result, the effective area of the membrane in the SWFO is used to be decreased, which leads to a decrease in the water flux [19]. The performance of the SWFO module can also differ depending on the diameter and length of the module because the number of membrane leaves and length of the flow path are different [20]. However, as stated earlier, there is no study on the plate-type FO element. Thus this study is first evaluating the plate-type FO element under different structural parameters and operational conditions.

In this paper, an element-scale plate-type FO process operates under two different operational modes: FO and PAFO. First, the effect of the plate-type FO element structure on the flow resistance and relationship between the flow rate and inlet pressure (both FS and DS side) were studied. Various operating conditions, such as temperature of FS and DS, flow rate, and DS concentration tested in the FO mode and PAFO mode such as water flux and RSF were also evaluated. Moreover, a suitable operating condition for the PAFO mode was investigated by applying a hydraulic pressure to the FS side. The objective of this study is to find useful information for the long term implementation of a full-scale FO system using the plate-type FO element.

2. Materials and methods

2.1. Plate-type FO element

A commercially available plate-type FO element (Porifera, Hayward, CA, USA) was used in this study. Fig. 1 shows the schematic diagram of the plate-type FO element. The flow pattern of the plate-type FO element showed a counter-current flow pattern, so two solutions flowed on both sides of the element. The plate-type FO element had a standard configuration, and the effective area of the plate-type FO single element composed of fourteen membrane sheets was 7 m^2. The AL of the plate-type FO single element faced the FS, and then the SL of the element faced the draw solution (FO mode).

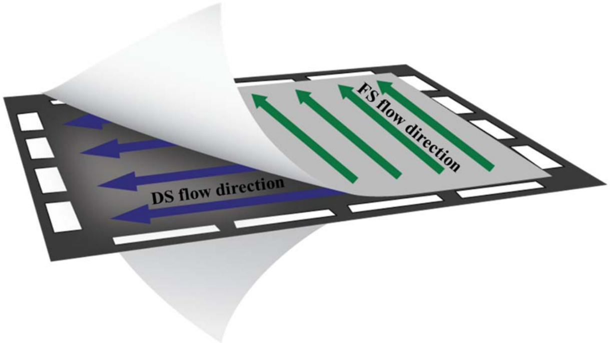

Fig. 1. Illustration of the flow-path of a plate-type FO single element.

2.2. Pilot-scale experimental set-up and procedure

As shown in Fig. 2, a pilot-scale FO (or PAFO) system was used for the experiment. Plate-type FO single element tests were conducted under various operating conditions, as given in Table 1. To analyze the performance of the FO and PAFO, the DS concentration, flow rates of both sides, and hydraulic pressure on the feed side were changed. Flow meters were installed in three places except for the end of the FS, and the pressure gauges were installed at both the inlet and outlet of the element. The electrical conductivity was measured using an electrical conductivity meter (Orion 4 Star, Thermo Scientific, Albany, USA) to calculate the RSF and salt rejection rate. Two chillers and an electric heater with temperature controllers were used to set both the FS and DS at the desired temperature. Both the FS and DS were recirculated back into each solution tank, and the volumes of both the FS and DS were 330 L. An overflow tank and a weight level transmitter were installed next to the FS and DS tanks to measure the water flux, and all data were recorded including the pressure, flow rate, electrical conductivity, and weight level of the overflow tank (to calculate the water flux) at a 1 min interval.

For the PAFO experiments, the following applied pressures were employed: 0.5, 1.0, and 1.5 bar. The feed pressure changed by adjusting the back pressure valve for the fixed feed and draw flow rates. In the PAFO mode, the flow rate was different from the FO mode because the maximum applicable flow rate decreased by applying the hydraulic pressure. Application of 0.5–1.5 bar might be difficult to define as “PAFO” but in most of pilot-scale studies, 0.3–1.2 bar could be applied due to both structural and instrumental limitations [15]. In this case, both terms, “PAFO” and “additional hydraulic pressure” are used.

2.3. Water flux and reverse salt flux (RSF) measurements

The water flux of the membrane was determined by measuring the change in the permeate volume weight using a weight level transmitter in the overflow tank (Eq. (1))

$$J_w = \frac{W_1 - W_0}{A \times \Delta t} \tag{1}$$

where J_w is the membrane water flux, W_1 and W_0 are the initial weight and weight at time t of the FS, respectively, t is the time interval, and A is the effective area of the membrane.

The change in concentration in the FS at the beginning and end of each experiment was measured. The RSF (J_s, GMH) was then calculated using Eq. (2)

$$J_s = \frac{C_f V_f - C_i V_i}{A \times \Delta t} \tag{2}$$

where J_s is the RSF, C_i and C_f are the initial and final salt concentrations of FS (g/L), respectively, and V_i and V_f are the initial and final volumes of the FS (L), respectively. When tap water was used as an FS, the RSF was determined by measuring the increase in electrical conductivity of the FS between the start and end of the pilot-scale experiment.

3. Results and discussion

3.1. Baseline performance and effects of the plate-type structural configuration

The plate-type FO element has two inlets – FS and DS – due to the characteristics of an osmotically driven process. Both the FS and DS entered the FO element and two streams of concentrated and diluted solutions occurred from the element [17]. Hence, two flow paths exist on the FS and DS sides of the membrane, with spatially variable properties that may be strongly interelated. Therefore, this study first evaluated how each flow rate affects the other flow rates by changing the flow rate, and second, how each inlet pressure affects the other inlet