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Forward osmosis using dimethyl ether as a draw solute

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HIGHLIGHTS

- Aqueous dimethyl ether was used as a draw solution for forward osmosis experiments.
- Forward osmosis phenomena were observed in both U-tube and cross-flow tests.
- Osmotic pressure of aqueous dimethyl ether did not follow the van't Hoff equation.
- Water permeated from feed to draw solution with a flux of 2.12–2.91 $L \cdot m^{-2} \cdot h^{-1}$.

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ABSTRACT

Forward osmosis experiments were carried out using an aqueous dimethyl ether solution as a draw solution. The osmotic process was examined using membranes (U-tube and flat cell) with differing effective membrane areas. Water permeation was confirmed to proceed from an aqueous feed solution composed of 0.5 wt.% sodium chloride to the draw solution through a forward osmosis membrane. Any dimethyl ether remaining in the draw solution after the forward osmosis process could be volatilized simply by leaving the solution at room temperature. Experimental results using the draw solution proposed in this study indicate the potential of the forward osmosis process as a convenient water recovery system by the energy only of the pressurizing injection of dimethyl ether.

1. Introduction

Drinking water is an essential human need. Accordingly, methods toward the desalination of seawater and brackish water, as well as reclamation of sewage and industrial water, have become crucial areas of research to address current and impending global fresh water shortages. A number of processes are currently in use for this purpose, including distillation [1,2] and reverse osmosis membrane methods [3,4], among others. The "forward osmosis (FO)" method [5–7] is drawing attention from researchers as a promising new water treatment technology. In this method, water in a treated solution, called a "feed solution" (FS), permeates through a semi-permeable FO membrane to a high-osmotic pressure solution, called a "draw solution" (DS) due to differences in osmotic pressure between the FS and DS, eliminating the need for an external energy source. However, in terms of water recovery from the DS, external energy is necessary for separation. Therefore, some ideas for solutes comprising the DS medium have been proposed from the viewpoint of efficient water recovery methods with low energy consumption. Multivalent ions [8,9], sugars [10], alcohols [11], magnetic nanoparticles [12], and water-soluble low-boiling gases [13] have been proposed as DS solutes for the FO method. Proposed DS materials—except for water-soluble low-boiling gases—have to be treated by passage through membranes (e.g., reverse-osmosis (RO) and nanofiltration (NF) membranes) for water recovery from the DS after an FO operation. In such cases, electrical power is necessary to operate a high-pressure pump for membrane filtration processes.

Alternatively, for cases in which water-soluble low-boiling gases are used as the DS, the medium can be simply heated after an FO operation to remove dissolved volatiles to recover water. Heating energy is therefore necessary for the methods proposed above, as some source of thermal energy is needed for producing fresh water from the DS after an FO operation; consequently, there is a possibility that FO methods cannot be differentiated from the RO process, which is a conventional method for desalination. The investigation of different solutes and conditions in order to decrease energy consumption for water recovery from the DS is thus the key objective of FO research and development for the reasons above.

In this paper, we report the results of our investigation of a dimethyl ether (DME) aqueous solution as a potential DS for FO applications. We focused on DME as a DS solute because of its desirable physical properties, namely high water solubility and high volatility.

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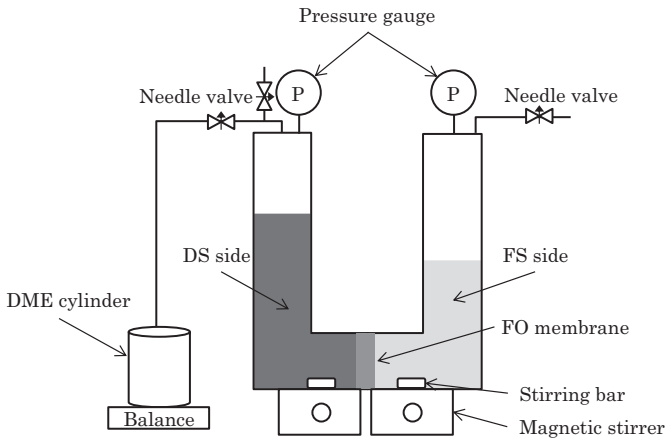

Fig. 1. Schematic of square-type U-tube equipment for FO operations.

DME is reported that toxicity to the living body is extremely low because peroxide is not generated and it resolves in the atmosphere [14,15]. Then, DME is applied to the dryness of coal and the dehydration of the sewage sludge [16,17].

These characteristics of DME should allow for the generation of high osmotic pressure and recovery of water from the DS with minimal energy input.

2. Experimental

2.1. Materials

Experimental setups for U-tube and membrane cell FO operations are shown in Figs. 1 and 2, respectively. The SW30 membranes used as FO membranes in this study were obtained from Dow Chemical Co., Ltd. The activated layer of the FO membrane was placed facing the DS side in the FO cell for all FO operations. An aqueous sodium chloride solution (0.5 wt.% NaCl) was used as the FS for all experiments. DME gas (>99.0%, GC grade) was purchased from Tokyo Chemical Industry Co., Ltd.

2.2. FO operation using a square-type U-tube

A square-type acrylic U-tube with an effective membrane area of 10.7 cm^2 used for FO operations is illustrated in Fig. 1. The DME aqueous solution (19.9 wt.%) used as the DS was made by dissolving DME gas (50 g) in ion-exchanged water (200 g) at an inlet DME gas cylinder pressure of ca. 0.3 MPa. The DS was injected into the DS side of the cell, and after that, the inlet valve of the DS side was closed. The DS and the FS were magnetically stirred for 217 min at 25 °C after the initial osmotic pressure of the DS was measured.

2.3. FO operation using a flat-sheet membrane cell

A flat-sheet C10-T type membrane cell (Nitto Denko Ind. Co., Ltd.) with an effective membrane area of 60 cm^2 was used for the cross-flow type FO operation as shown in Fig. 2; a flow pass height of 0.7 mm was used and a mesh that causes turbulent flow was included. The DS was prepared by injecting DME gas (37.4 g) from the DME cylinder into ion-exchanged water (500 g) to obtain a 7.0 wt.% DME aqueous solution in the DS side of the cell, and after that, the inlet valve of the DS side was closed. Thereafter, both the DS and FS were circulated for 1 h by counter flow at pass speeds of 320 $mL \cdot min^{-1}$ for both solvents. During the FO operations, the temperatures of the DS and FS were 17 °C and 25 °C, respectively. The weight of dissolved DME in ion-exchanged water was calculated by the difference in the weight of the DME gas cylinder before and after the operation.

The osmotic pressure of the aqueous solution was measured by the freezing point depression method using a trace-amount manual OM-806 osmometer (Vogel GmbH & Co. KG).

3. Results and discussion

3.1. FO operations

For FO operations using the square-type U-tube (Fig. 1), water permeation from the FS side to the DS side was observed under the following conditions: inner FO cell pressure of 0.34 MPa on the DS side, and initial DS and FS osmotic pressures of 985 mOsm (2.40 MPa) and 179 mOsm (0.43 MPa), respectively. The flux value in the FO operation was 2.12 $L \cdot m^{-2} \cdot h^{-1}$. Despite the DS being under a pressure of 0.34 MPa, water permeation from the FS to the DS could be confirmed, indicating that the FO phenomenon arises from osmotic pressure of the DS containing a DME solute in this case. We postulated from this result that DME aqueous solutions could be used as the DS in FO processes; accordingly, we decided to conduct an FO operation using the flat-sheet FO cell (Fig. 2). The test conditions and results using the flat-sheet cell are shown in Fig. 3. The value of the inner cell pressure was 0.12 MPa. The initial osmotic pressures for the DS and FS were

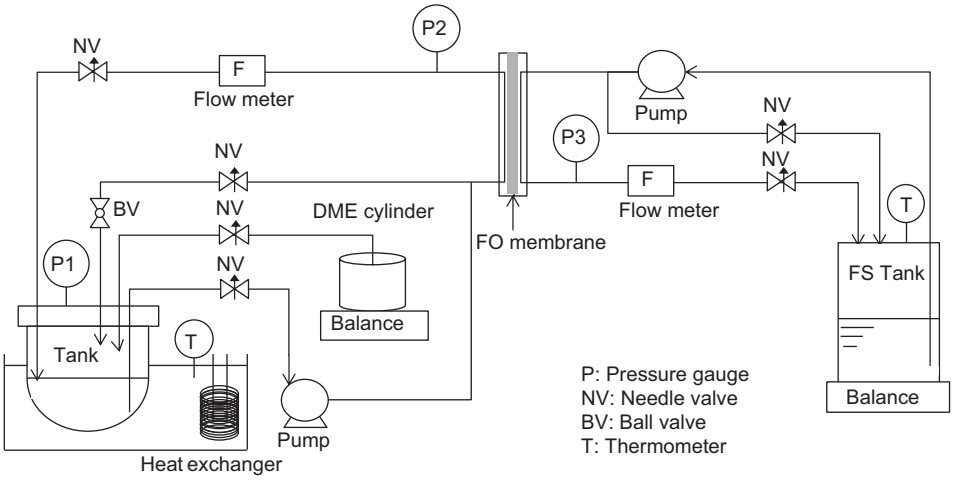

Fig. 2. Schematic of cross-flow system for FO operations.