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Mathematical model of flat sheet membrane modules for FO process: Plate-and-frame module and spiral-wound module

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ABSTRACT

The forward osmosis process is considered a promising desalination method due to its low energy requirement compared to other methods. In this study, modelling and simulations for a plate-and-frame and a modified spiral-wound module are carried out for the FO process. The mathematical models consist of mass balance, a permeate flux model, and concentration polarization equations. The plate-and-frame model is formulated with consideration of flow directions, and the modified spiral-wound model is formulated with consideration of its geometric characteristics. These two sets of model equations are numerically and iteratively integrated since they are implicit and highly non-linear. The simulation for both modules was conducted by varying 4 types of operating conditions: volumetric flow rate of the feed and the draw solution, the concentration of the draw solution, flow direction, and the membrane orientation. The results for various conditions are also compared. In future research, the developed model could be applied for designing FO modules and finding optimal operating conditions.

1. Introduction

Global water shortage has been an important issue in past decades as the population has increased drastically, and many researchers have tried to solve this problem through sea water desalination. Many desalination methods have been practiced and researched so far. Due to the high cost of membranes in the past, thermal methods such as Multi-Effect Distillation (MED) and Multi-Stage Flash (MSF) processes were widely used. However, membrane-based methods by forward osmosis (FO) and membrane distillation (MD) as well as reverse osmosis (RO) have been spotlighted in recent days since they require less energy than the thermal methods and the membranes are now readily available [1]. Of the membrane-based methods, the FO process has recently received considerable attention. This is because it does not require any external energy for separation such as hydraulic pressure in RO process and sensible heating energy in MD process. The FO process simply separates water from saline water by introducing a more concentrated solution than sea water in the opposite side of a semi-permeable membrane. As a result, water permeation occurs through the membrane between two solutions in trans-membrane direction [1,2].

Compared to the other desalination processes, the FO process has distinct advantages: it does not require thermal resources, which makes the membrane-based method superior to the thermal ones. Moreover, unlike the RO process, it proceeds spontaneously without the application of hydraulic pressure by a high pressure pump; consequently, it also uses less energy than the RO process and the operational equipment used in the FO plant is much simpler because there is no need for additional pressure handling equipment. In addition, the merits of not applying hydraulic pressure include a lower propensity for membrane fouling and a higher rejection of salts [3–6,21].

Despite the advantages of the FO process, limitations still exist. One of the major concerns is the selection of the more concentrated solution than sea water, called "draw solution" [7,8]. After passing through the membrane process, the water product is recovered from the diluted draw solution through an extra separation process and the re-concentrated draw solution is sent to the membrane process again for recycling. Therefore, the draw solution should be carefully chosen with respect to non-toxicity and easy recovery. Furthermore, the separation process also needs to be attentively designed with consideration of the low energy use and the uncomplicated separation procedure for the draw solution. The development of the unique membrane and the membrane module to FO process should also be paid close attention [6,9–13,22]. In particular, concentration polarization that causes the flux reduction in the RO process also happens both at the external surface of the membrane and inside of the membrane structure (ECP and ICP). Since the internal concentration polarization (ICP) caused by asymmetric membranes plays significant role in the flux reduction in the FO process, unlike in the RO process, the desired characteris-

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