STUDIES ON OSMOTICALLY DRIVEN MEMBRANE PROCESSES FOR POWER GENERATION AND DESALINATION

ATTARDE DINESH SHASHIKANT

DEPARTMENT OF CHEMICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI
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by

ATTARDE DINESH SHASHIKANT

Department of Chemical Engineering

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CERTIFICATE

This is to certify that the thesis entitled "**Studies on Osmotically Driven Membrane Processes for Power Generation and Desalination"** being submitted by **Mr. Attarde Dinesh Shashikant** to **Indian Institute of Technology Delhi** for the award of the degree of **Doctor of Philosophy** is a bonafide record of original research work carried out by him under my guidance and supervision in conformity with rules and regulations of the institute.

The results contained in it have not been submitted in part or full to any other university or institute for award of any degree/diploma.

Dr. SHARAD KUMAR GUPTA

Professor

Department of Chemical Engineering

Indian Institute of Technology Delhi

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(Attarde Dinesh Shashikant)

ABSTRACT

Pressure retarded osmosis (PRO) and forward osmosis (FO) are osmotically driven membrane processes and emerging as viable processes for capturing clean energy and producing fresh water from sea water, respectively. Critical problems restricting the application of these processes are the accurate design and analysis of the membrane module or module configurations. Hence, the module-scale mathematical models are developed in this study to predict the performance of osmotically driven membrane processes. Two types of modules such as spiral wound module and hollow fiber modules are used for this study.

Transport phenomena through the active layer of the membrane is described by using the Spiegler Kedem theory in parallel to the traditionally used solution-diffusion theory. The film theory is used to describe the mass transfer near to the active layer of the membrane, so called as external concentration polarization. Using a classical convective-diffusion equation, the mathematical model is proposed for defining the mass transport in the support layer of the membrane, so called as the internal concentration polarization. The mass balance and pressure drop equations are obtained to incorporate the spatial variations of flow variables for both the feed as well as the draw solution sides. The finite difference method is employed to solve the coupled algebraic and ordinary differential equations. A combination of two non-linear optimization techniques is used with module-scale mathematical models and experimental data points to estimate the unknown parameters of the model. These estimated parameters are then used to predict the performance of FO and PRO at some other operating conditions and validate the mathematical model. The experimental results obtained by the modules matched well with the model predictions.

If the model uses Spiegler-Kedem (SK) model for describing the mass transport through the active layer of the membrane, it is referred to as the SK based model. On the other hand, if the

solution diffusion model is used for describing the membrane mass transport, it is referred to as the SD based model. It is tried to answer the question, whether the Solution Diffusion (SD) based model or the SK based model is better for design and analysis, and for obtaining the optimal operating conditions for both FO as well as PRO applications. The product recovery and the energy extraction efficiency of the spiral wound module at variety of operating conditions are also analyzed. Relatively 10 to 20 % lower flux / power density is observed on the module-scale as compared to that on a membrane test cell.

The osmotically driven membrane process, such as pressure-retarded osmosis (PRO) and forward osmosis (FO), assisted reverse osmosis (RO) hybrid systems are being emerged for the low-energy cost seawater desalination and wastewater treatment, and the simultaneous RO brine (or RO concentrates) management. These hybrid systems are also evaluated in the present work. The earlier studies in literature have considered the spiral wound type of module in these hybrid systems. However, as per an economic point of view, the hollow fiber type of modules could be superior due to their unique feature of high surface area per unit volume (i.e., packing density) and, thus, are used in the current work to evaluate the hybrid systems. For commercialization of the hybrid systems, a big concern is that how much energy per unit product (i.e., specific energy) can be saved due to the hybrid systems as compared to the most preffered conventional stand-alone RO technique. Unlike the previous proposed models for the evaluation of the hybrid systems, the models used here consider the coupling between the solute and solvent, the concentration polarization phenomena and the spatial variations of flow variables (such as velocity, concentration, and hydraulic pressure) in the module. The unknown mass transport parameters in the models for the RO are obtained from the literature, and those for the FO / PRO are predicted by using the experimental data reported in the literature.

Using the proposed models, the specific energy saving in the seawater desalination and simultaneous wastewater treatment by using the hybrid systems are compared with the conventional RO system for various RO recoveries. The simulation results obtained by the models for hybrid systems show that the greater the percent dilution in FO / PRO, the higher is the specific energy saving in the hybrid systems. For an RO recovery of 50 % and FO / PRO dilution of 40 %, it is found that around 25 % specific energy saving may be realized in both the hybrid systems as compared to the conventional RO system at studied operating conditions. Interestingly, the results also reveal that as the RO recovery increases, the specific energy saving increases for the FO-RO hybrid system but decreases for the RO-PRO hybrid system.

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