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Evaluation of fouling potential and power density in pressure retarded osmosis (PRO) by fouling index

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HIGHLIGHTS

- The influence of fouling on the PRO process was investigated under various conditions.
- Correlations between the fouling and power density and efficiency in PRO process were suggested.
- MFI was proposed to be a fouling index for PRO process.

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ABSTRACT

Pressure retarded osmosis (PRO) is an osmotically-driven membrane process to utilize salinity gradient power (SGP), which is renewable energy originated from the different salt concentration between seawater and fresh water. However, PRO suffers from membrane fouling, leading to decreased water permeability and energy density. Although prediction of fouling is important for its mitigation and control, little information is available on fouling potential in PRO process. Accordingly, this study aims at the investigation of fouling propensity of PRO membranes under different conditions. Feed solutions that have different fouling potential were used in a laboratory-scale PRO system. Silt density index (SDI) and modified fouling index (MFI) were applied as indicators for assessing PRO membrane fouling. Results showed that the power density of PRO decreases with an increase of the fouling potential of the feed waters. MFI was proposed to be a fouling index for PRO because it showed a better correlation with the power density than SDI and turbidity. When MFI value is lower than 1400 s/L^2, the efficiency is higher than 70%, indicating that 30% loss in energy recovery compared to the case with D.I. water. This suggests that pretreatment requirements for PRO may be determined based on MFI results.

1. Introduction

There are growing demands to search renewable sources of energy because the possibility for depletion of conventional energy resources such as fossil fuels has continuously increased. Solar, wind, geothermal energy, and biomass are four emerging renewable energies [1]. Nevertheless, they currently make up very small fraction of total energy consumption. The depletion of energy also affects water security because energy and water are closely related [2]. Energy is used to produce water from various sources and water is used in hydropower generation or in thermal power generation as coolant.

Recently, salinity gradient power (SGP), which is the renewable energy from the different salt concentration between seawater and fresh water, has drawn attention as a new approach to produce energy from water [3]. Due to the large amount of seawater on earth, the potential for SGP is huge. Moreover, SGP is not affected by climate change, and it is less sensitive than other renewable energies because it only relies on the salinity of seawater [4–7]. Accordingly, this is a promising method to supply sustainable energy.

One of the ways to utilize SGP is pressure retarded osmosis (PRO) [4, 8]. PRO uses an osmosis membrane to convert chemical potential into hydraulic pressure. The osmotic pressure between fresh water and seawater is approximate 24 bar. In fact, the optimal working pressure of PRO process is approximate half of this, 11 to 14 bar, which is used to operate a turbine or a generator [9,10]. PRO process could be also applied to recover energy from brine of reverse osmosis (RO) process. In this case, PRO can not only use osmotic power in RO brine but also mitigate a problem related to disposal of high salinity brine into sea and ground. Therefore, it has potential for improving efficiency of seawater desalination plants.

Nevertheless, there is a major problem in terms of membrane fouling in applying PRO for energy production or recovery [4,11,12]. Membrane fouling is a common problem in all membrane-based processes.

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Nomenclature

J_w	Water flux (Lm^{-2} h^{-1})
A	Water permeability\
A_0	Initial membrane permeability
$\Delta\pi$	Osmotic pressure
ΔP, P	Hydraulic pressure
η	Solution viscosity
R_f	Fouling resistance
α	Specific cake resistance
m_c	Cake mass
S_m	Membrane area
ϕ	Degree of concentration polarization by cake layer formation
t_i	Initial time
t_f	Final time
Cs	Bulk concentration of the foulants

Fouling on membrane surface decreases water permeability through PRO membrane and shortens lifespan of the membrane. As a consequence, the operation and maintenance costs are significantly increased by membrane fouling. In PRO process, fouling also results in a reduction in power density.

Accordingly, understanding the fouling behavior in the PRO process is greatly important. In PRO process, both sides of the membrane meet two solutions having different properties: the active layer is exposed to fresh water such as river water or reclaimed wastewater, and the support layer is exposed to high salinity water such as seawater or RO brine [9]. Fouling mainly occurs on the active layer side because the fresh water may contain the foulant such as colloidal, organic matters and so on [13,14]. Therefore, there is a critical need for a systematic understanding of the fouling behavior on the feed side of the PRO membrane, and for the development of strategies for fouling prediction during operating PRO process [15,16].

The main objective of this study is to investigate fouling propensity of PRO membranes under different conditions. The specific objectives of this study are 1) to evaluate the effect of feed water quality on flux decline and power density in PRO process, 2) to compare the accuracy of fouling prediction by three methods including turbidity, SDI (silt density index), and MFI (modified fouling index), and 3) to propose a guideline for pretreatment of feed solution of PRO process for its stable operation.

2. Theory

2.1. Pressure retarded osmosis process

Pressure retarded osmosis (PRO) is an interesting technology to obtain osmotic power from the contact of two solution streams having different salinities (fresh water and seawater). In PRO process, water transports across a semi-permeable membrane from a low salinities stream (fresh water and feed water) to a pressurized high salinities stream (seawater and draw solution), and then it produces a power that is equal to the product of hydraulic pressure and water [9,17]. The movement of water from a low salinity solution into a pressurized high salinity solution through a semi-permeable membrane is retarded by a high pressure pump [9]. This process changes the osmotic pressure into a mechanical energy (water power), whose power is equal to the product of water permeation rate and applied pressure [9]. The mechanical energy can be subsequently changed into electric energy by hydro-turbine [18].

In using a semi-permeable membrane permeating only water except other solute and ions, theoretically, the water flux in an osmosis process can be described universally as Eq. (1) [14,18].

$$J_w = A(\Delta\pi - \Delta P) \tag{1}$$

where J_w is the water flux (Lm^{-2} h^{-1}); A is the water permeability; $\Delta\pi$ is the osmotic pressure; and ΔP is the hydraulic pressure. This equation describes the diffusive transport of water through a membrane material [4]. In a PRO process, the energy production is indicated by a power density. The power density is proportional with the product of the water flux and the hydraulic pressure (applied pressure) on high salinities solution across the semi-permeable membrane [9,18]. The power density in PRO process can be described as Eq. (2).

$$W = J_w\Delta P = A(\Delta\pi - \Delta P)\Delta P = A\Delta\pi\Delta P - A(\Delta P)^2 \tag{2}$$

Thus, the osmotic pressure is converted into mechanical energy based on Eq. (2). When the volume of the fluid is constant in PRO process, the internal energy is changed by applied pressure in the draw solution, and then the energy in form of osmotic pressure is converted to be kinetic energy that can be running hydro-turbine.

When fouling occurs, the flux is gradually decreased. Using the resistance-in-series model, the following equation can be derived:

$$W = \frac{1}{\frac{1}{A_0} + \eta R_f}(\Delta\pi - \Delta P)\Delta P \tag{3}$$

where A_0 is the initial membrane permeability; η is the solution viscosity; and R_f is the fouling resistance.

If the fouling occurs mainly due to cake layer formation, the Eq. (3) can be adjusted as:

$$W = \frac{1}{\frac{1}{A_0} + \frac{\eta\alpha m_c}{S_m}}(\Delta\pi - \Delta P)\Delta P \tag{4}$$

where α is the specific cake resistance; m_c is the cake mass; and S_m is the membrane area. The Eq. (4) implies that the power density of the PRO process is inversely proportional to the mass of foulant deposits.

Particle deposition on PRO membrane may result in cake-enhanced concentration polarization as well as an increase of hydraulic resistance [13]. In this case, the effective osmotic pressure decreased due to this concentration polarization. Thus, the Eq. (4) may be modified to account for this effect.

$$W = \frac{1}{\frac{1}{A_0} + \frac{\eta\alpha m_c}{S_m}}(\Delta\pi\phi - \Delta P)\Delta P \tag{5}$$

where ϕ is the degree of concentration polarization due to cake layer formation, which has a value ranging from 0 to 1. In this case, the pressure for maximum power density is changed from $\Delta\pi/2$ to $\Delta\pi\phi/2$.

2.2. Membrane fouling index

2.2.1. Silt density index (SDI)

Silt density index (SDI) is a well-known index for a measurement of the fouling potential of particulate matter in RO process. According to the ATM standard method, SDI is measured by dead-end filtration (0.45 μm, disk membrane, Millipore) [19]. SDI is calculated by initial time (t_i) required to collect the 500 ml sample; final time (t_f) required