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Pressure-retarded osmotic power system model considering non-ideal effects

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ABSTRACT

A model for pressure-retarded osmotic (PRO) power systems is described. The model considers several non-ideal phenomena including internal and external concentration polarization, local variation due to mass transfer, pressure losses along membrane surfaces and other losses throughout the system. This provides an overview of many of the major dynamics that must be considered in PRO power modeling. The model is validated by comparison to experimental data available in the literature. The model is used to investigate the effect of feed and draw flow rates, and of hydraulic pressure difference on PRO system performance. These parameters can be controlled by the system operator and can be set so as to minimize competing non-ideal effects. Improvements in net power of up to 7× are observed when best operating parameters are used as opposed to other values used in the literature.

1. Introduction

Electricity can be generated at a concentration gradient. This means that all over the world, where rivers meet oceans there is a potential for electricity generation. The global potential for this energy is estimated at 2.6 TW [1]. This potential can be exploited via several processes including pressure-retarded osmosis (PRO) [2].

At the heart of a PRO power system is a semi-permeable membrane. Feed solution (e.g. freshwater) and draw solution (e.g. seawater) are circulated on opposite sides of the membrane. The osmotic pressure difference that exists between the fluids (as a function of their concentration difference) drives the feed water to permeate through the membrane over to the draw side. If a hydraulic pressure is applied to the draw side, the permeate rate will decrease but its hydraulic pressure will rise to match the applied draw side pressure. In other words, osmotic pressure will be converted to hydraulic pressure. The pressurized permeate can then be used to drive a turbine and generate electricity.

The idea of generating electricity by mixing freshwater and seawater was first proposed by Pattle [3] and the first osmotic energy converter system design was proposed by Norman [4]. It was Loeb [5–7] however who pioneered the technology, conducting the first experimental verifications of the concept and introducing the basic PRO power system design that is used today. Over the last several years the number of publications on the subject has risen sharply [8]. In 2009 the first salinity gradient power plant was put into operation by the company Statkraft with a designed capacity of 10 kW [9].

Improving PRO power is a matter of reducing non-ideal effects and their influence on power. Non-ideal effects include concentration polarization, decreasing concentration gradient along the membrane length, pressure losses along the membrane length and throughout the system, and electrical and mechanical losses in the system components. This paper provides an overview of the theory behind each of these non-ideal effects and presents a model with consideration for all of them. This provides one of the most comprehensive PRO power system models that is available in the literature [10–17]. The model is validated against experimental data.

Non-ideal effects can be minimized by adjusting the hydraulic pressures and flow rates at which the system is operated [14,18]. The challenge however is that non-ideal effects are inversely proportional with respect to one another. For example, external concentration polarization can be reduced by increasing flow rates (and hence velocities) however this also leads to an increase in pressure losses.

In order to identify the best operating parameters, the proposed mathematical model is used to simulate PRO performance under variable conditions. Results indicate that best operating parameters

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vary as a function of the particular site conditions, equipment specifications and membrane properties. In the cases considered, it is observed that by selecting best operating hydraulic pressures and flow rates, net power output can be increased as compared to output when rule of thumb operating parameters are used. Net power densities of 1.33 and 5.08 W/m^2 are achieved for two different membranes, when best operating parameters are used.

2. Methodology

2.1. Pressure-retarded osmosis

Consider a semi-permeable membrane with feed flow rate Q_F on one side and draw flow rate Q_D on the other, as illustrated in Fig. 1.

The resulting water permeate flux J_W (permeate flow rate per unit membrane surface area) will be a function of the osmotic pressure difference across the membrane $\Delta\Gamma$, minus the hydraulic pressure difference ΔP applied to the draw side:

$$J_W = A \times (\Delta\Gamma - \Delta P) \tag{1}$$

where A is the membrane's water permeability.

$\Delta\Gamma$ is the driving force behind the phenomenon of osmosis and is estimated as a function of concentration difference Δc and temperature T:

$$\Delta\Gamma \approx i_v \times R_g \times T \times \Delta c / M \tag{2}$$

where R_g is the universal gas constant, M is the molar mass of the salt and i_v is the van't Hoff coefficient, which is equal to the number of ions in the solution. In the case of NaCl, $i_v = 2$ and $M = 58.44$ g/mol.

The resulting power density w (power per unit membrane surface area) developed across the membrane can be calculated by:

$$w = \Delta P \times J_W \tag{3}$$

From equations (1) and (3) w can be written as a function of ΔP. Setting the equation equal to 0 and differentiating with respect to ΔP the maximum point on the ideal power density curve is identified at $\Delta P = \Delta\Gamma/2$. The maximum power density w_{max} is therefore given by:

$$w_{max} = A \times \Delta\Gamma^2 \big/ 4 \tag{4}$$

The relationship is summarized in Fig. 2 where w (normalized over w_{max}) is plotted against the ΔP (normalized over $\Delta\Gamma$). The figure also shows the cases of reverse osmosis (RO) where $\Delta P > \Delta\Gamma$, forward osmosis (FO) where $\Delta P = 0$, and pressure-assisted forward osmosis (PAFO) where $\Delta P < 0$.

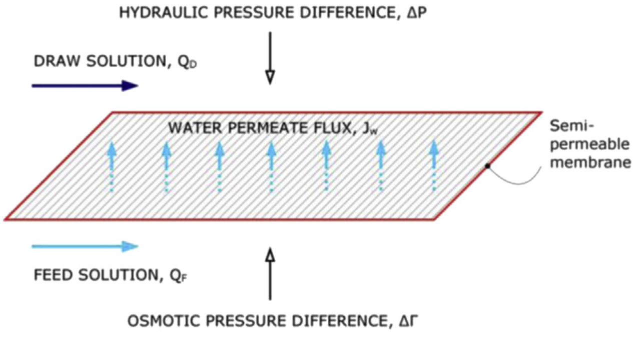

Fig. 1. PRO across a semi-permeable membrane.

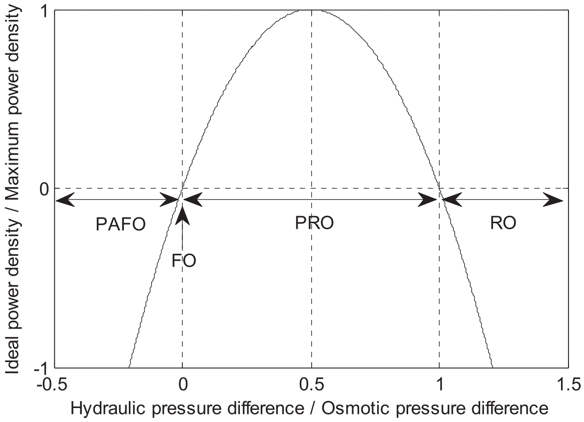

Fig. 2. Ideal power curve (normalized).

2.2. Concentration polarization

As water permeates through the membrane a thin film of diluted solution is developed on the draw side of the membrane surface. Also, the membrane is not perfectly impermeable to salt, and the resulting salt permeate creates a thin layer of concentrated solution on the feed side of the membrane surface as well as across the membrane's support structure, which is generally oriented towards the feed side. This effect is referred to as concentration polarization. The resulting concentration difference across the active membrane layer is therefore significantly reduced from the bulk difference Δc_b to the effective difference Δc_m. It is this effective concentration difference that determines $\Delta\Gamma$ and that drives J_W.

As described by Naguib et al. [19], by solving the equilibrium equation between permeate flux and the rate of dilution it is possible to define the steady-state Δc_m as a function of feed and draw bulk concentrations $c_{F,b}$ and $c_{D,b}$:

$$\Delta c_m = \frac{c_{D,b} \times \exp\left(\frac{-J_W \times \delta_D}{D_D}\right) - c_{F,b} \times \exp\left(J_W \times \left(\frac{\delta_F}{D_F} + \frac{\lambda}{D_S}\right)\right)}{1 - \frac{B}{J_W}\exp\left(\frac{-J_W \times \delta_D}{D_D}\right) + \frac{B}{J_W} \times \exp\left(J_W \times \left(\frac{\delta_F}{D_F} + \frac{\lambda}{D_S}\right)\right)} \tag{5}$$

where B is the membrane's salt permeability and λ is the support structure thickness.

This provides an expression for Δc_m that considers internal concentration polarization (ICP) (across the support layer) as well as external concentration polarization (ECP) (across both the feed and draw boundary layers). This same expression is derived by McCutcheon and Elimelech [11], Achilli et al. [13] and by Yip et al. [15], however in those cases polarization across the feed boundary layer was neglected. In that sense this expression provides additional accuracy, although it is minor because the feed side film is generally very thin [19].

The feed side δ_F and draw side δ_D boundary layer thicknesses can be calculated by:

$$\delta = \frac{D}{K} \tag{6}$$

where K_F and K_D are the feed and draw diffusion transfer coefficients respectively, which can be calculated from Refs. [20,21]:

$$K = 3 \times 1.86 \times \left(\frac{u \times D^2}{L \times d_h}\right)^{\frac{1}{3}} \tag{7}$$

where L is the membrane length, d_h is the hydraulic diameter of the flow path and u is the cross-flow velocity.