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Feasibility of osmotic power from a hydrodynamic analysis at module and plant scale

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ABSTRACT

A hydrodynamic mass transfer model for a pressure retarded osmosis (PRO) power plant is developed to investigate the technical feasibility of such a power plant. The key element is a 2D model at the membrane level, which accounts for the actual size of the membrane sheets. This model enables the computation of salinity gradients along both sides of a membrane sheet, from which the local membrane flux is calculated.

Integration of the membrane flux across a membrane sheet yields the trans membrane flow rate in an entire module. The novelty of this paper is the determination of the performance of an osmotic power module from the 2D hydrodynamic mass transfer model. The developed numerical model can be calibrated against lab measurements and, more importantly can be used for reliable extrapolation of the membrane performance to the module and plant scale.

On the membrane level, the results are comparable to lab scale results from literature. However, the power output for real size membranes is about 40% lower than for lab scale membranes. Furthermore, counter-current flow gives an approximately 15% larger power output then co-current flow for real size membranes. The maximum gross power output that can be obtained with commercially available membranes is about 4.5 W/m^2. The optimum net power output is 0.5 MW/(m^3/s) for BWRO membranes. If hollow fiber membranes can be used and salt water pre treatment can be removed the power output can be 0.92 MW/(m^3/s).

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1. Introduction

Due to a growing demand on electric power, the scarcity of fossil fuels and the associated CO_2 release, new energy sources are required. One of these renewable energy sources is salinity gradient power via Pressure Retarded Osmosis (PRO). In the PRO process, fresh water flows through a membrane from a low hydrostatic pressure to a high hydrostatic pressure due to the osmotic pressure difference. A turbine converts the increase in potential energy into electrical energy. Loeb first developed this idea in the 1970s [1]. PRO has since then been under investigation.

1.1. In many papers

On the feasibility of PRO, the presented results are based on small laboratory size membranes and expected power outputs, leading to optimistic conclusions and overestimation of the potential of PRO, as shown in this paper. The goal of this paper is to investigate if it is technically feasible to produce power which commercially available membrane modules. For this purpose a 2D-numerical hydrodynamic mass transfer model is developed. The model focuses on flat sheet membranes only. The results are discussed in Sections 5–8. The 2D model results are compared with laboratory experiments carried. Secondly, results on commercially available modules are presented. The results show large difference between the membrane performance at the lab and module scale. Therefore, the author proposes to further develop numerical models and perform experiments at the module scale in order to extract sustainable power from salinity gradients.

2. Description of a PRO power plant

Fig. 1 shows an overview of a PRO Power Plant (PROPP) or Osmotic Power Plant (OPP). Fresh water and salt water are supplied in co- or counter-current flow direction to both sides of the membranes. Part of the fresh water will flow to the salt-water side decreasing the salinity and osmotic pressure. The salinity on the

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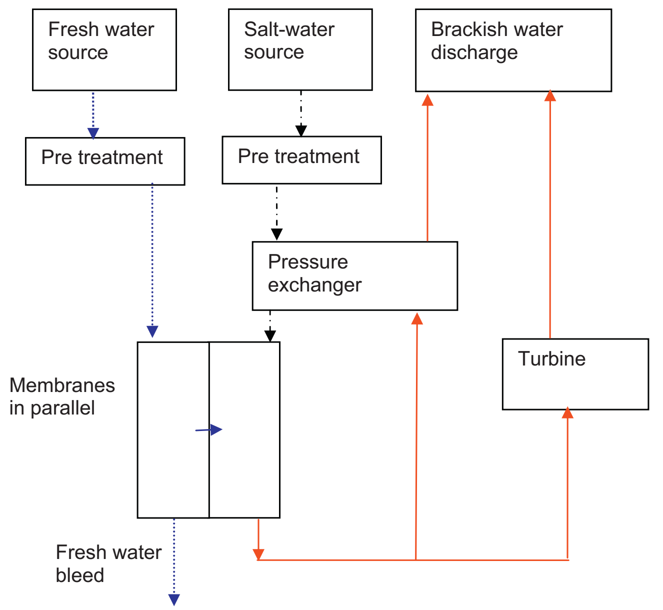

Fig. 1. Overview of a PROPP (blue, dotted = fresh water; black, dotted-dashed = salt water; red, solid = brackish water). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

fresh waterside C_f will increase due to the diffusive salt flux and water flux through the membrane. The flux of fresh water decreases along the membrane. To prevent an accumulation of salt on the membrane (external concentration polarization) a certain cross flow velocity is required to enable proper mixing. This will result in a bleed flow at the fresh waterside.

The high-pressure brackish-water outflow from all membranes diverges into two parts. One part feeds the turbine and generates electric power; the other part is used to pressurize the incoming salt water by means of a pressure exchanger. The volumetric flow rate into the turbine equals the total fresh water flow rate through the membranes. The brackish water outflow from the low-pressure side of the pressure exchanger and the turbine are combined into the brackish water discharge.

Commercially available flat sheet RO modules have three connections: inflow of salt water, outflow of salt water and outflow of fresh water (permeate tube). To use a module in PRO a fourth connection is required to enable a fresh water cross flow. Fig. 2 shows an example how this can be achieved. A plug is separating the two sides of the permeate tube. By applying a special glue layer (red lines in Fig. 2) the fresh water flow is directed parallel to the salt-water flow. It is assumed for this paper that the given configuration is feasible.

The module and PROPP performance are characterized by a number of output variables: gross power output, net power output, number of membranes per module. The environmental conditions (C_f and C_s) and the design parameters optimize these output variables. The following design parameters are included in the optimization process:

1. Salt water inflow velocity,
2. Bleed velocity on fresh water side of the membrane,
3. Trans-membrane pressure.

In the next section the calculation model is described, which uses these input parameter to calculate the performance of a PROPP.

3. Numerical model of a single membrane sheet

The gross power output (E_{gross}) of a plant can be determined by:

$$E_{\text{gross}} = \eta_t Q_m \Delta P \tag{1}$$

in which, η_t is the efficiency of the turbine, Q_m is the fresh water flow through the membrane and ΔP is the trans membrane pressure difference. The fresh water flow rate through the membrane is calculated from:

$$Q_m = n \int_{A_m} J_w(y)\, dA_m \tag{2}$$

in which n is the number of parallel membrane modules, J_w is the local water flux through the membrane, A_m is the area of the membrane. The water flux, can be described by [2]:

$$J_w = A\left[\pi_s \frac{1-(C_f/C_s)\exp(J_w K)}{1+(B/J_w)(\exp(J_w K)-1)} - \Delta P\right] \tag{3}$$

A is the water permeation coefficient, B is the salt permeation coefficient, C_f is the salt concentration on the fresh water side and C_s the salt concentration on the salt water side; π is the osmotic pressure of the salt water. The K-parameter is the porous substrate resistance to salt diffusion and is related to the structure parameter, S of [3] by:

$$K = \frac{S}{D} \tag{4}$$

in which D is the diffusion coefficient of salt in the support layer. S is given by:

$$S = \frac{t\tau}{\eta} \tag{5}$$

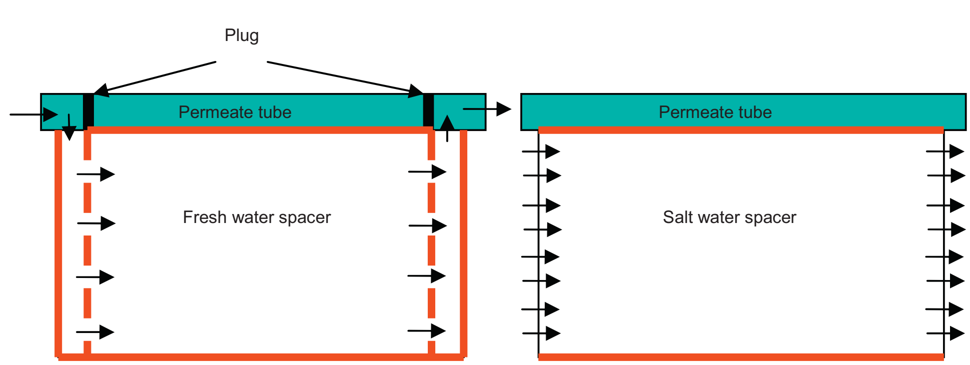

Fig. 2. Example of the module design for the use of commercially available RO modules in PRO. Left hand side fresh unfolded water spacer, right hand unfolded side salt water spacer. The arrows denoted the flow direction of the fresh water, the red lines show the glue lines. The salt water flow is the same as for a commercially available RO module. The membrane is attached on each side of the fresh water spacer. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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