Applied Energy 164 (2016) 425–435

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Experimental investigation of pressure retarded osmosis for renewable energy conversion: Towards increased net power

Jonathan Maisonneuve [a,*], Claude B. Laflamme [b], Pragasen Pillay [a]

[a] Department of Electrical and Computer Engineering, Concordia University, 1455 de Maisonneuve W., Montreal, Quebec H3G 1M8, Canada
[b] Hydro-Québec Research Institute, Hydro-Québec, 600 de la Montagne, Shawinigan, Quebec G9N 7N5, Canada

HIGHLIGHTS

- Gross power densities of 7.1 W/m^2 are obtained from a commercial membrane.
- The influence of non-ideal effects on gross power and net power is analyzed.
- Usual test conditions yield low net power and are unsuitable for energy conversion.
- Adjustment of operating conditions leads to significant improvements in net power.
- A mathematical model is described and agrees well with experimental data.

ARTICLE INFO

Article history:
Received 6 July 2015
Received in revised form 4 November 2015
Accepted 4 December 2015
Available online 23 December 2015

Keywords:
Energy conversion
Salinity gradient power
Pressure retarded osmosis
Operating conditions
Net power density

ABSTRACT

An experimental and theoretical investigation of pressure retarded osmosis (PRO) performance was conducted. The characteristic parameters of a commercial membrane were determined experimentally. Gross power density of up to 7.1 W/m^2 was obtained, which is among the highest reported in the literature for a commercial membrane. The effect of operating conditions on membrane performance was also investigated. Results show that under typical test conditions, concentration polarization and spatial variations are minimized, but the resulting pressure losses due to friction lead to net power densities that are negative. Test conditions that favor net power density, and hence that are more appropriate for energy conversion applications, were identified. Under these conditions net power density of up to 4.5 W/m^2 was observed.

1. Introduction

Salinity gradients are a large untapped source of renewable energy [1]. Salinity gradients exist in natural estuaries where rivers meet oceans, in coastal settlements where wastewater is released into oceans, and in desalination plants where super-concentrated brine is released into the ocean [2–4]. Currently, this energy is dissipated into the environment as heat and entropy, but several processes have been developed for harnessing this energy and converting it to electricity [5]. One such option is pressure retarded osmosis (PRO) [6].

In PRO a hydraulic pressure is applied to a volume of concentrated 'draw' solution, which is introduced to one side of a semi-permeable membrane. When a volume of diluted 'feed' solution is introduced on the other side of the membrane, osmosis will cause water to permeate from the feed side to the draw side. The expanding volume of high-pressure draw solution can be depressurized across a turbine and generator to produce electricity. Fig. 1 shows the basic concept of an osmotic power plant. The draw solution is pressurized via the pressure exchanger. A complete osmotic power plant would also include pre-treatment filters to minimize membrane fouling.

The concept of PRO was proposed as early as 1974 [7–9] and gained momentum in 2009, with the development of the first PRO prototype in Norway, which signaled a milestone in the technology's development [10]. It was recognized that membrane development was among the most important barriers to commercialization and the target of achieving membrane power densities of 5 W/m^2 was proposed [11–13]. Membrane power density is a measure of the power that can be generated over a certain area of membrane surface. It is a useful measure of performance because high power densities will reduce capital cost and improve cost effectiveness of the installation. Recent laboratory results of newly developed hand-cast membranes have surpassed the 5 W/m^2 target [14,15].

---

* Corresponding author. Tel.: +1 514 848 2424x4126.
E-mail addresses: j_mais@encs.concordia.ca (J. Maisonneuve), laflamme.claude@lte.ireq.ca (C.B. Laflamme), pillay@encs.concordia.ca (P. Pillay).

http://dx.doi.org/10.1016/j.apenergy.2015.12.007
0306-2619/

Nomenclature

A	water permeability ($\mathrm{m\,s^{-1}\,Pa^{-1}}$)
a_m	membrane surface area ($\mathrm{m^2}$)
B	salt permeability ($\mathrm{m\,s^{-1}}$)
c	concentration ($\mathrm{g\,l^{-1}}$)
D	salt diffusion coefficient ($\mathrm{m^2\,s^{-1}}$)
d_h	hydraulic diameter (m)
F	turbulence correction factor
f	friction factor
h	channel height (m)
J_s	salt permeate flux ($\mathrm{kg\,s^{-1}\,m^{-2}}$)
J_w	water permeate flux ($\mathrm{m^3\,s^{-1}\,m^{-2}}$)
k	mass transfer coefficient ($\mathrm{m\,s^{-1}}$)
L	channel length (m)
P	hydraulic pressure (Pa)
R	salt rejection ratio
Re	Reynolds number
S	structure parameter (m)
Sc	Schmidt number
Sh	Sherwood number
T	temperature (K)
u	cross-flow velocity ($\mathrm{m\,s^{-1}}$)
$\dot{V}$	volumetric flow rate ($\mathrm{m^3\,s^{-1}}$)
W_{gross}	gross power density ($\mathrm{W\,m^{-2}}$)
W_{net}	net power density ($\mathrm{W\,m^{-2}}$)
w	channel width (m)

Greek symbols

α	constant
Γ	osmotic pressure (Pa)
γ	constant
δ	boundary layer thickness (m)
ρ	density ($\mathrm{kg\,m^{-3}}$)

Subscripts

b	bulk
D	draw
F	feed
m	membrane
P	permeate
s	salt
w	water

In evaluating and comparing power densities, it is important to recognize that operating conditions used during testing have a significant influence on results [16–18]. Membranes are tested under a variety of operating conditions, however it has been proposed that flow rates be set such that cross flow velocities approach 0.25 m/s [19]. The advantage of operating at relatively high flow rates such as these is that non-ideal effects, like external concentration polarization and spatial variations in concentration and flow, are minimized [20]. The disadvantage is that parasitic pressure losses from friction in the membrane module and system piping will increase significantly. These losses are rarely reported in the literature, and yet they can outweigh the advantages of operating at high flow. Consequently, it is unlikely for similar flow rates to be used at the commercial scale, and for reported power densities to be realized. Moreover, the relationship between membrane performance and operating conditions is non-linear, meaning that membranes which perform well at high flow rates may not necessarily be the ones that perform well at low flow rates.

In this study the effect of operating conditions on power densities is investigated with consideration for parasitic pressure losses. A mathematical model for PRO that was previously described in [20,21] is validated experimentally. The terms *net power density* and *gross power density* are used to distinguish between performance when parasitic pressure losses are included and neglected, respectively. Performance at operating conditions suggested in the literature is compared against performance at operating conditions that yield maximum net power density.

2. Theory

2.1. Water and salt flux in pressure retarded osmosis

The basic relationship that describes water permeate flux J_w across a semi-permeable membrane is:

$$J_w = A \cdot (\Delta\Gamma - \Delta P) \qquad (1)$$

A is the membrane water permeability, ΔP is the hydraulic pressure difference across the membrane, and $\Delta\Gamma$ is the osmotic pressure difference across the membrane. Osmotic pressure is a function of concentration and temperature [22].

From Eq. (1) it is clear that to maximize water permeate flux it is desirable that the membrane be highly permeable. In practice however, this is limited by the competing desire to minimize salt

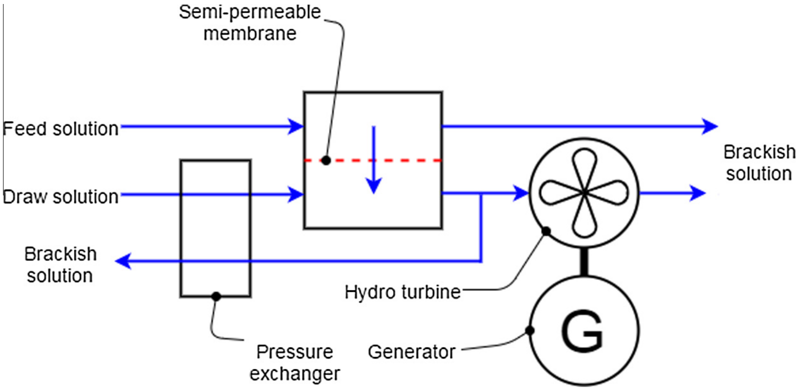

Fig. 1. Concept for osmotic power plant.