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Osmotic power potential in remote regions of Quebec

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ABSTRACT

Diesel-generated electricity is currently used to supply electricity to community micro-grids in remote regions of Quebec. Given its high cost and environmental impact there is interest in developing renewable energy alternatives for such applications. The potential of pressure retarded osmotic (PRO) power to supply remote community loads is investigated here. A mathematical model for PRO power systems is described and the effects of concentration polarization, spatial variation, pressure losses and system inefficiencies are reviewed. The model is used to simulate the PRO power potential of 10 selected rivers given there variations in temperature, concentration and flow rate throughout the year. Power potential is compared to electricity loads of nearby communities. In each case, only a small percentage of the river's lowest monthly flow rate would be required to satisfy the peak power demand of the micro-grids. This suggests that osmotic power could serve as a reliable source of electricity in such applications.

1. Introduction

The energy released by mixing a volume of freshwater with a much larger volume of seawater is equal to 0.66 kWh per m^3 of freshwater (2.37 kJ/l) (when the temperature of the solutions $T = 5\ ^\circ C$ and the concentration difference $\Delta c = 30\ kg/m^3$). This is equivalent to the osmotic pressure difference $\Delta\Gamma = 23.7$ bar as defined by Ref. [1]. Pressure retarded osmosis (PRO) is one process by which this energy can be harnessed [2–4].

By bringing freshwater and seawater (or any other combination of diluted and concentrated solutions) into contact across a semi-permeable membrane, PRO makes use of the tendency of freshwater to move towards seawater as driven by $\Delta\Gamma$. The process is illustrated in Fig. 1. In PRO some hydraulic pressure ΔP is applied against $\Delta\Gamma$ such that water permeate flux J_w across a semi-permeable membrane is reduced (or retarded). Water permeate flux (flow rate per unit of membrane surface area) is given by:

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

where A is the membrane's water permeability, which is a function of its micro-structure. The net gradient $\Delta\Gamma - \Delta P$ is towards the seawater side and the result is that flow is against the applied hydraulic pressure. The result is an additional volume of water J_w with hydraulic pressure ΔP. The product of the two yields the power density w (power per unit membrane surface area):

$$w = J_w \cdot \Delta P \tag{2}$$

From (1) and (2) it can be shown that maximum power density occurs when $\Delta P = \Delta\Gamma/2$ [6]. In other words, there is a theoretical limit to the power that can be harnessed through PRO. When $\Delta P = \Delta\Gamma/2$ only half of the total energy available can be harnessed which gives 0.33 kWh/m^3 (1.19 kJ/l) ($T = 5\ ^\circ C$ and $\Delta c = 30\ kg/m^3$). Non-ideal membrane effects and system inefficiencies further reduce the energy which can be harnessed to an estimated 27% of the total available energy of mixing.

PRO technology remains in the research and development stages, with only one power generating prototype having been built to date in the world [7]. Advances in PRO membranes and pressure exchangers are required. While PRO is an estimated 20 years away from becoming an economically viable renewable energy option for mainstream markets, there are certain niches where the technology may find earlier application [8]. This article considers the particular case of PRO potential in remote communities of Quebec, Canada.

Although most of Quebec is supplied by a well-developed hydro-electric network, there are 30 remote communities that rely on locally supplied micro-grids. There are 22 micro-grids in all

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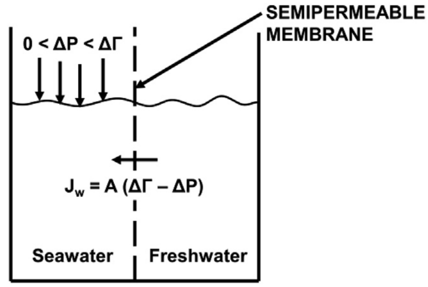

Fig. 1. Pressure retarded osmosis [5].

throughout the province (19 diesel-powered, 2 hydro-powered and 1 powered by fuel oil). While the main grid supplies electricity at prices between 0.05 and 0.10 $/kWh, in certain micro-grids rates reach over 1.00 $/kWh [9]. Also, the diesel-generated electricity has a much larger carbon footprint and local emissions reduce air quality.

For these reasons there is interest in developing cleaner and less expensive renewable energy systems for these remote communities. Plans have been announced to develop wind-diesel hybrid systems in several locations but these have yet to materialize [9]. Other studies have suggested the potential for hydrokinetic power [10]. Salinity gradient power offers another option with several advantages. One of the main advantages is its stability. While variations in wind speed and to a lesser degree river speed are rapid and unpredictable, variations in concentration and temperature are minor and very gradual, generally occurring over the space of several months. Also the land use footprint of PRO has been estimated at 0.043 km^2/MW, which is comparable to solar, 6 times less than wind and 8 times less than hydroelectricity (with reservoirs) [11].

This paper reviews the fundamental principles of PRO power system modeling and then uses the model to evaluate the PRO energy potential of 10 rivers that are situated within close proximity to 9 of the remote micro-grids throughout Quebec. The energy potential is compared to the micro-grid loads and a discussion of options for matching loads and sources is presented.

2. Osmotic power for remote micro-grids in Quebec

2.1. Micro-grids in Quebec

Quebec's 22 remote micro-grids are shown on the map in Fig. 2. They are located mainly along the northern coastline of the province, in the Nunavik region. Others are found on the Îles-de-la-Madeleine and Île-d'Anticosti in the Gulf of Saint-Lawrence and in the Basse-Côte-Nord region. Grids in the Shefferville and Haute-Mauricie regions are unique in that they are land-locked. For the most part these regions are only accessible by airplane and therefore fuel supplies must be flown in.

Table 1 provides an overview of energy use for each of the micro-grids, showing the annual use, peak demand and average price of electricity [9,12]. The 3 dominant grids are Lac-Robertson and Schefferville which are hydro-powered and Cap-aux-Meules which is powered by fuel oil. Among the diesel-powered grids, the largest loads are Kuujjuaq (annual load of 18.4 GWh and peak demand of 3.45 MW) and La Romaine (annual load of 13.1 GWh and peak demand of 3.23 MW). Akulivik, Aupaluk and Ivujivik have the highest electricity prices of 1.10, 1.19 and 1.32 $/kWh respectively. Equivalent CO_2 emissions for the diesel and fuel oil grids are also shown. Since osmotic power produces no greenhouse gas emissions during operation, using it to replace diesel-power would reduce the equivalent CO_2 emissions.

2.2. Freshwater and seawater resources

Most of the communities in question are located in the Nunavik and Basse-Côte-Nord regions. These are regions that have significant freshwater and seawater resources. Seawater resources include the Hudson Bay (average T = 0 °C and c = 30 kg/m^3), the Ungava Bay (average T = 1 °C and c = 32 kg/m^3) and the Gulf of Saint-Lawrence (average T = 0 °C and c = 32 kg/m^3) [13–15]. In each case a moderate seasonal variation in temperatures and concentrations can be observed. Consider for example the Ungava Bay at a depth of 50 m, near the community of Kuujjuaq. As shown in Fig. 3, temperature varies ±0.5 °C with a peak in the fall. Concentration varies ±1 kg/m^3 with a peak in the spring.

Fig. 3 also shows the impressive seasonal variation in flow rates of the Koksoak River, also near the community of Kuujjuaq. This variation is a function of the freeze/thaw cycle and is characteristic of northern rivers throughout Quebec. In addition to these seasonal changes, daily variations in flow rates can be observed at up to 50 km inland of the Ungava Bay due to very strong tides. These tides also lead to variations in river concentration. For the sake of the present study tidal variations are ignored. In reality however, the influence of tides will reduce the concentration gradient at the estuary and may require moving water over large distances, which increases the capital expenses and pumping losses.

Historical flow rate data for Quebec rivers is available from Ref. [16] and [17]. The average monthly flow rates for the last 5 years available in the database were used to evaluate the power potential of each river. The period over which data was used for each river is specified later on in the results section, together with the energy potential.

3. Modeling pressure retarded osmotic power

3.1. Ideal pressure retarded osmotic power system

The basic processes involved in PRO power can be illustrated by considering the ideal system shown in Fig. 4. Seawater (draw solution) with flow rate Q_D is pressurized to ΔP. It is introduced on one side of a membrane unit while freshwater (feed solution) with flow rate Q_F is introduced on the other side. By PRO, freshwater permeates to the seawater side with flow rate Q_p and with hydraulic pressure ΔP. This pressurized flow can power a generator, while the balance of flow can be recycled to power the pump (assuming 100% equipment efficiencies). Non-ideal dynamics which operate on the membrane unit are explained in the following sections.

3.2. Concentration polarization

Consider a single capillary from a hollow-fiber membrane as shown in Fig. 5. The capillary is composed of a thin active layer of thickness θ and a porous support structure of thickness λ. Freshwater flows on the inside of the capillary and seawater on the outside. Because the membrane is not perfectly impermeable to salt, there will be a reverse salt flux J_s (from the seawater side to the freshwater side) given by:

$$J_s = B \cdot \Delta c \tag{3}$$

where B is the membrane's salt permeability which is a function of its micro-structure.

As salt permeates to the freshwater side it takes times for it to mix evenly with the bulk solution. The result is a thin layer of concentrated solution (with thickness δ_F) on the inside surface of the porous substructure and an accumulation of concentrated