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Reverse electrodialysis: Comparison of six commercial membrane pairs on the thermodynamic efficiency and power density

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ABSTRACT

Reverse electrodialysis (RED) generates electricity through the entropy increase from the mixing of sea and river water. Two important RED process parameters were investigated: power density (in Watts per square meter membrane) and the thermodynamic efficiency. Beside this, we quantified losses in a RED stack experimentally: co-ion transport, osmosis and internal loss as a function of current density and related those to the energy loss due to mixing. Six different commercial available membrane pairs – *Qianqiu Heterogeneous Ion Exchange Membrane* (AEM and CEM), *Qianqiu Homogeneous Ion Exchange Membrane* (AEM and CEM), *Fumasep* (FKD and FAD), *Selemion* (AMV and CMV), *Neosepta* (ACS and CMS) and *Neosepta* (AMX and CMX) – were compared. It was found that at maximal power density, the thermodynamic efficiency was between 14% and 35%, where 50% is the maximum theoretical value at maximal power density. The highest score (35%) is achieved with the Neosepta (ACS-CMS) pair. The power density of the different membrane pairs varied from 0.5 to 1.2 W/m^2. The maximal value was found for Fumasep (FAD and FDK) and Selemion (AMV and CMV) pair. For ranking purpose, we have combined the two response parameters to a single one by multiplying the power density and the thermodynamic efficiency. This response parameter is the highest (34 W/m^2 %) for the Selemion (AMV and CMV) pair.

1. Introduction

Salinity power, using river and sea water, is a clean and sustainable source of energy. One of the technologies for generating energy from this source is reverse electrodialysis (RED). The basic theory of RED is described by different authors in the literature [1–18]. A RED stack consists of alternating CEMs (cation exchange membranes) and AEMs (anion exchange membranes). These membranes are separated by spacers that keep the membranes in a fixed position, ensure defined water compartments and act as turbulence promoters. Through the spacer compartments is alternately river and sea water is supplied. Positive charged ions diffuse from the sea water to the river water through the CEMs in one direction and negative charged ions diffuse through AEMs in the other direction. These ionic currents are converted in an electron current at the electrodes of the stack by proper redox reactions. Power can be withdrawn by connecting an external load to these electrodes. Maximal power is delivered if the resistance of the external load equals the internal stack resistance.

Theoretically, the maximal amount of energy that can be harvested from 1 m^3 fresh water and a large surplus salt water (30 g NaCl/L) is 2.55 MJ [14]. However, transport of large amounts of sea water to and through the stack consumes a large amount of energy. Therefore, it is more realistic to mix 1 m^3 fresh water with 1 m^3 sea water, generating 1.76 MJ [14]. In the Netherlands, the Rhine has an average flow rate of 2200 m^3/s and has a power potential (P_{pot}) of 3.9 GW, about 30% of the electricity consumption in the Netherlands. The amount of produced power by RED depends on the availability (Q) of the river water and on the energy efficiency of the process. The fraction of the theoretical maximal energy that can be obtained from given volumes salt and sweet water with given concentrations is the energy efficiency Y. Therefore, the total generated power is $P = QYP_{pot}$. It is clear that energy efficiency is a key parameter in the RED process.

In this article, we focus on the energy balance during the RED process at maximal power. In order to obtain a maximal power density, relative high flow rates are used and a low degree of mixing is achieved. At these circumstances, the energy efficiency Y – the produced energy in relation to the exergy of the feed – is low and rather useless. Therefore, we introduce the term 'thermodynamic efficiency' (η_T) which is defined as the produced energy in relation to the difference of exergy of the incoming and outgoing

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water. The second key parameter is the power density P_d, the generated amount of power per square meter of membrane. It is a measure of the power per invested euro because the membranes (and spacers) form a substantial part of the price of a RED power plant.

In fact power density and energy efficiency interact in a conflicting way. If only electrical aspects are taken into account, it can easily be seen that for maximal power density the external resistance (the load) is equal to the internal resistance of the stack. Therefore, the energy efficiency cannot exceed 50% [13]. The RED process is most energy efficient at low current densities when the external resistance is much higher than the stack resistance. High power densities demand a maximal concentration difference over the membrane. This can be achieved with high flow rates, which is limited by an increase in pump power [14]. Therefore, there exists an optimal flow rate for maximal energy efficiency.

Many authors studied the power density of a RED stack [2,3,8,9,14–16]. In these studies no systematic approach on the effect of membrane properties on the total performance was made. Długołęcki et al. [18] presented a theoretical model of the power density in relation to spacer thickness, area resistance of the membranes and permselectivity of the membranes. They concluded that a high power density could be obtained with small membrane spacing and low membrane resistance. Our goal is to compare different commercial membrane pairs in a real RED stack and relate the measured power density and energy efficiency of mixing from a RED stack to the membrane properties (area resistance and permselectivity).

2. Experimental

2.1. Endplates

The RED stack that was used in our experiments is shown in Fig. 1. This experimental setup is described in great detail in earlier publications [13,14]. Electrode compartments are situated inside the endplates. Endplates were milled from reinforced phenol formaldehyde (Epratex HGW 2082, Eriks, The Netherlands). Stainless steel bolts were used to close the stack.

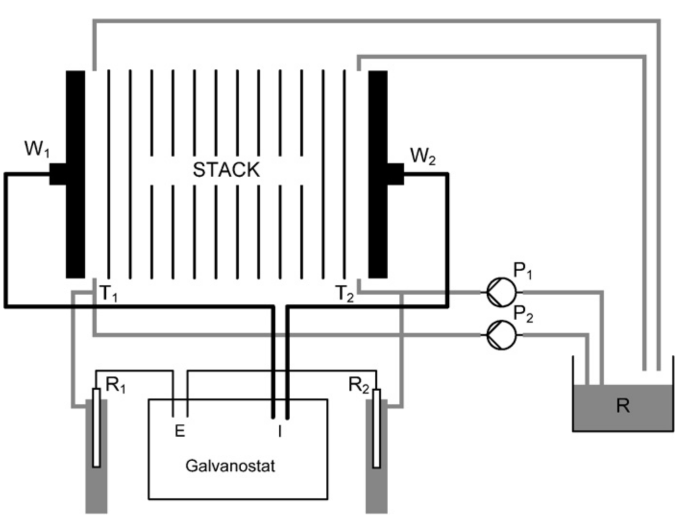

Fig. 1. Configuration of the experimental set-up. The electrode rinse R is circulated with pumps P_1 and P_2 to the electrode compartments of the stack. The Ag/AgCl reference electrodes R_1 and R_2 are inserted in two vessels which are connected to the inlets with the T-connectors T_1 and T_2. The galvanostat is electrically connected to the reference electrodes R_1 and R_2 and to the working electrodes W_1 and W_2. The river and sea water flows through the stack are not shown.

2.2. Cells

The functional area of one membrane was 100 cm^2. On the outsides of the stacks CEMs were used. The studied ion-exchange membranes were:

(a) Qianqiu Heterogeneous Ion Exchange Membrane AEM and CEM (Hangzhou QianQiu Industry Co., China)
(b) Qianqiu Homogeneous Ion Exchange Membrane AEM and CEM (Hangzhou QianQiu Industry Co., China)
(c) Fumasep FKD and FAD (Fumatech, Germany)
(d) Selemion AMV and CMV (Asahi Glass Company, Japan)
(e) Neosepta ACS and CMS (Tokuyama Corporation, Japan)
(f) Neosepta AMX and CMX (Tokuyama Corporation, Japan)

The radius of the feed and drain channels through the membranes was 4 mm. The stacks were equipped with nylon woven spacers with a thickness of 200 μm (Nitex 03-300/51, Sefar, The Netherlands). Gaskets were made of silicon micro-film with a thickness of 200 μm (SSF-MLTN-940, Specialty Silicone Fabricators, Paso Robles, USA). Stacks were made with 25 cells (Fumasep and Qianqiu homogeneous) or 5 cells (the other membrane pairs). The membranes, spacers and gaskets were made at their correct size by means of a punch and a press.

2.3. Electrode system and electrical measurements

The electrode compartments contained a NaCl solution of 15 g/L (technical grade; Frisia Salt, Harlingen, The Netherlands). For the anode and cathode compartment a separate electrode rinse circuit was used with a common supply vessel (Fig. 2). The anolyte and catholyte flow rate was about 100 mL/min. Titanium mesh end electrodes, coated with Ru–Ir mixed metal oxides with dimensions of 10 cm × 10 cm were used (Magneto Special Anodes, Schiedam, the Netherlands. These electrodes are suitable as anode as well as cathode and therefore current reversal is allowed. Ag/AgCl gel filled reference electrodes (QM711X, ProSense, Oosterhout, the Nether-

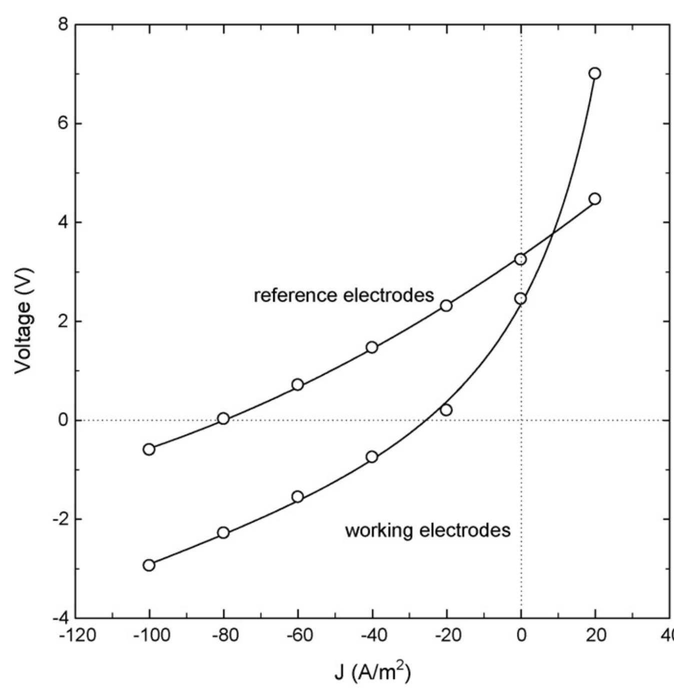

Fig. 2. Voltages as function of the current density J of a RED stack with 25 cells with Fumasep membranes.