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Pressure drop in reverse electrodialysis: Experimental and modeling studies for stacks with variable number of cell pairs

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ABSTRACT

Reverse electrodialysis (RED) is a sustainable technology for salinity gradient energy harvesting. In order to make the process economically competitive, it is desirable to operate it at the highest possible net power density, which depends on the RED stack geometry and on the pressure drop along its pathways and, thus, on the energy spent for solutions pumping. The fluid flow in RED stacks generally occurs in rectangular compartment channels, equipped with spacers. The effects of spacers design and properties have been studied extensively in recent years. However, the other possible causes for a RED stack and their relative impact on the process performance have not yet been systematically studied. In this study the partial pressure drops in (1) distribution ducts, (2) branches, (3) beams, (4) due to sudden section expansion between the beam and the compartment channel and (5) in the compartment channel were taken into consideration. A model for the total pressure drop inside a RED stack, with a parallel fluid flow distribution through the compartments, is proposed and experimentally validated for lab-scale RED stacks with sheet flow spacers and compared with an open channel (spacer-free) design. The importance of each partial pressure drop was then evaluated quantitatively through model simulations for industrial-scale stacks with an increasing number of cell pairs. It was found that the net power density decreases when the cell-pair number increases, since the partial pressure drop in the branches becomes dominant. Moreover, the possible reasons for a non-uniform fluid flow distribution are discussed, thus making the proposed model useful for planning and/or optimization of RED stacks design.

1. Introduction

Salinity gradient energy, first time described in 1954 [1], is classified as a renewable, sustainable and clean energy source [2–6]. It is based on an energy release, when two aqueous streams of different salinity are mixed. The process does not produce emissions which may interfere with the global climate change; the fuel cost is none; and via the continuous Earth's cycle of water (evaporation/precipitation) this source is non-periodic, thus a stable power supply can be guaranteed.

The chemical energy associated with solvation of salts can be quantified in terms of Gibbs' free energy. For example, the global power of salinity gradient energy due to rivers' discharge into the oceans has been estimated to be in the range from 1.4 to 2.6 TW [6,7]. However, at random mixing of the solutions, the system quickly reaches chemical equilibrium, without providing sufficient time to capture the released energy [3]. To harvest a salinity gradient energy (through controlled mixing of aqueous streams of different salinity), several membrane-assisted technologies have been proposed so far: pressure retarded osmosis (PRO) [8,9], capacitive mixing (CAPMIX) [10,11] and reverse electrodialysis (RED) [12–14].

The advantage of RED is the direct conversion of chemical energy of salt solvation into electrical energy [15]. Through parallel flow compartments, formed by alternately arranged cation- and anion-exchange membranes, which are stacked between two electrodes, concentrated and dilute saline solutions are distributed, simultaneously. The resulting salinity gradient across the membranes leads to net movement of ions from the concentrated to the diluted saline solution. Ideally, perm-selective ion-exchange membranes would only allow the passage of the respective counter-ions, while excluding the flow of co-ions. Thus, the anions move through the anion-exchange membranes to the anode and the cations move through the cation-exchange membranes to the cathode. For electrical power generation, at the electrode compartments, a suitable redox couple converts the internal flux of ions into a flux of electrons via an external, conductive circuit connecting the anode and the cathode. In such a way, the power output of a RED stack depends on the potential difference, established between the two electrodes, and on the stack internal resistance.

It has been found that reduction in the RED stack channel's thickness and use of spacers can improve the fluid distribution

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[16], but it increases the pressure drop [17–19]. Reducing the flow rates of the two aqueous streams allows for a better fluid flow distribution and lower pressure drop [16,19], but it decreases the gross power density [18–23]. Therefore for characterization of the energy obtainable in a RED stack, the net power density parameter is used, which is estimated by subtracting the power spent for pumping from the gross power and normalized by the total membrane area [14,24].

In an optimized RED system the power spent for pumping can consume up to 25% of the total generated energy [25]. Even when a simplified stack geometry is considered, the demand for pumping power is significant compared to the generated energy, as shown by CFD studies [16,26]. Therefore correct estimation of pressure drop in RED stacks is crucial, since it directly affects the net power density of the system.

The classical approach to study the electrodialysis-related process has been to consider a single membrane pair as a repeating unit in the stack [27]. This approach does not take into account non-uniform fluid distribution inside the stack due to the pressure variation inside the stack [27]. The Hagen–Poiseuille or Darcy–Weisbach equations have been generally used to calculate pressure drop in flow compartments assuming a fully developed, uniform flow [18,28–30] and, therefore, equal pressure drop in all compartments. However, calculation of the net power density still depends on the experimental values of the pressure drop, as its theoretical values can be up to 20 times lower than the measured ones [18,30]. For example, in a 50 cell-pair RED stack, 80% of the experimentally determined pressure drop was found to be due to the contribution of the manifolds [25].

Moreover, the influence of the cell-pair number has been, so far, only studied experimentally in terms of the stacks' potential difference and internal electric resistance [22,25,26,31,32]. An almost linear dependence has been found with a slight deviation at higher cell-pair numbers, which was justified by ionic shortcut currents [31] or internal solutions leakages [26]. In case of a non-uniform fluid flow distribution through the compartments, simulated by CFD, the average gross power density was reduced by only 5% [26]. In such a way, if the resistance offered by the electrodes' compartments can be neglected, the generated RED stack power can be normalized by the total working membrane area and, thus, the gross power density becomes independent of the cell-pair number.

Through analyzing the current state-of-the-art on the RED technology, it can be therefore concluded that no systematic research has yet been performed, relating the number of cell pairs in a RED stack with the resulting pressure drop and its effect on the net power density.

In the present study, the effect of the cell-pair number on the pressure drop was evaluated both experimentally and through dedicated mathematical modeling. The proposed model was successfully validated with lab-scale RED stacks, composed by an increasing number of cell pairs with membranes separated either by sheet flow spacers or open (spacer-free) flow channels. Besides estimating the total RED stack pressure drop without significant deviations, the developed model provides guidelines for RED stack design, under non-uniform fluid distribution conditions. Since some of the so far ignored partial pressure drops are taken into consideration, a new, and quantitative, perspective over the cell-pair number influence on the net power density achievable in the RED process is presented.

2. Theoretical pressure drop model

The pressure drop in a RED stack depends on the solutions' flow rate and the geometry of the stack. Its estimation allows for determining the required power to pump the feed solutions, and therefore to obtain the net power density. Fig. 1 is a schematic representation of a possible plate-and-frame RED stack geometry with symmetrical design, in which the dilute and concentrated saline solution flows are separated, through equal number of

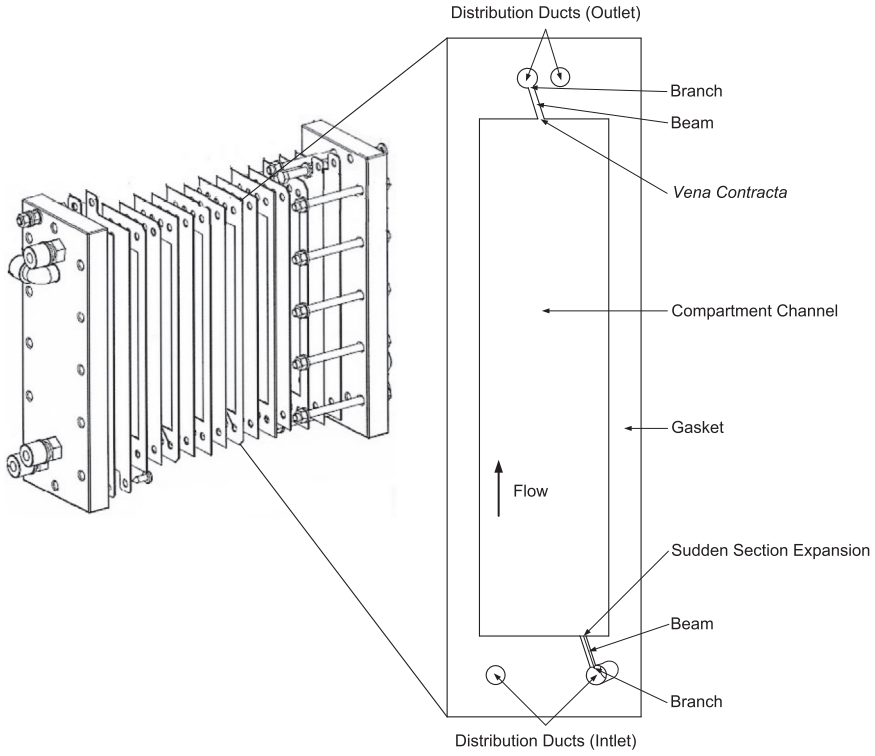

Fig. 1. Schematic representation of the studied RED stack geometry. (Adapted from the Technical Documentation of Electrodialysis unit EDR-Z-MINI of MEGA c.f.)