Performance analysis of reverse electrodialysis stacks: Channel geometry and flow rate optimization

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In this paper, the optimal channel geometry and flow rate of the concentrated and diluted solutions under the maximum net power output for the reverse electrodialysis (RED) stacks at a confined size are systematically investigated. A model considering the change in volume flow rate along the flow direction is employed to illustrate the process of the RED stack. For systematisms, under the maximum net power output, we first consider the optimal channel thicknesses at a given identical inlet flow rate and then the optimal channel thicknesses and flow rates. The profiles of flow rate, concentration, power density, and hydrodynamic loss along the flow direction are discussed. The net power output and energy efficiency for different membranes under the above two optimization situations are analyzed and compared. The results reveal that the optimal channel thickness of the high-concentration (HC) compartment is slightly larger than that of the low-concentration (LC) compartment for a given identical inlet flow rate. When both channel thickness and flow rate are optimized, the optimal channel thicknesses and volume flow rates of the HC compartment are, respectively, less than those of the LC compartment and the net power output and energy efficiency are significantly improved.

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1. Introduction

Recently, to alleviate the consumption of traditional fossil fuels, new and renewable resources have been explored and new utilization technologies have been developed [1,2]. Among them, salinity gradient power generation technologies such as pressure retarded osmosis (PRO) [3–5] and reverse electrodialysis (RED) [6–9] are the most appealing ones, and have been extensively investigated as they extract energy from solutions with different concentrations, which can be obtained from the sea water and river water that exit widely with vast amount throughout the world. Compared to the PRO system with a hydro-turbine, the RED system, which directly converts the Gibbs free energy of mixing into electricity through an ion-selective exchange membrane (IEM), contains no moving components, making it less demanding from operation and maintenance viewpoints.

Even though the RED system was first proposed in 1954 [10], it did not attract enough attention until the 21st century owing to the limited performance of IEMs. Now, IEMs with high performance and low cost are reliable, rendering it possible to install commercial electrical production plants. The first RED pilot plant was installed in southern Italy to extract energy from saline waters and concentrated brines with a power of up to around 40 W [11].

Besides experimental investigation of the performance of RED systems, numerical modeling and analyses also play important roles. The key points lie in describing the ion transfer process through IEMs. Many models have been developed based on the Nernst–Planck equation and mass and species conservation. Tedesco et al. [12] presented a multiscale mathematical model based on a mass balance and constitutive equation. Veerman et al. [13] proposed a 1D model to describe the RED process without considering changes in the volume flow rate along the flow direction. However, as the 1D model could not reflect the concentration polarization on the membrane–solution interface, which degraded the performance of the RED system, models with higher dimensions were further developed by solving the strongly coupled Nernst–Planck equation and the Navier–Stokes equations [14]. Long et al. [15] investigated the RED process in a bilayer nanochannel based on the Poisson–Nernst–Planck and Navier–Stokes equations. In another study, Long et al. [16] investigated the impacts of temperature gradient on ion transportation and power generation performance, and deduced a theoretical description to...
illustrate the energy conversion efficiency. Tedesco et al. [17] developed a simple 2D model by using the Nernst–Planck equation not only in the flow channels but also in the membranes.

Parameters impacting the performance of the RED system mainly include channel geometry and flow rate [18], membrane properties, fouling [19], multivalent ions [20], and electrodes [21]. Zhu et al. [18] reduced the pumping energy by using different tions in RED cells. Moya et al. [22] studied an RED stack with a rates of high-concentration (HC) and low-concentration (LC) solu-

... with different ion diffusive coef
... f... properties, fouling [19], multivalent ions [20], and electrodes [21].

... channel geometry and
... the diffusion boundary layer was systematically investigated, not only in the
... developed a simple 2D model by using the Nernst
... ... illustrate the energy conversion ef
... fluide reverse electrodialysis, and found that co-
... ion polarizability was the primary factor for co-ion effects on
... g... gated the effects of specific ions on the permeselectivity of sulfonated poly-cation exchange membranes, and found that co-

... Present literature on improving the performance of the RED system mainly focuses on effects of membrane properties such as pore size, permeselectivity, resistance, and diffusion coefficients on the performance of the RED system. The operation condition (vol-

... in the RED process is presented in the Appendix.

2.1. Performance specifi...的日志事件的行

... be equipped in a constrained space with a fixed cross-sectional area (W × L) and height (H), where W and L are the width and length of the RED stacks, respectively. The cell number \( N_{cell} \) of the stack is calculated by

\[
N_{cell} = \left\lfloor \frac{H - \delta_m}{\delta_H + \delta_L + 2\delta_m} \right\rfloor
\]

... where \([\_]\) is the rounding down operation, and \( \delta_m \), \( \delta_H \), and \( \delta_L \) are the membrane thickness, HC compartment thickness, and LC compartment thickness, respectively.

The RED voltage is calculated as [28]

\[
E_{cell}(x) = \frac{RT}{F} \ln \frac{\gamma_{Na}^{CH}(x)C_{CH}(x)}{\gamma_{Na}^{CL}(x)C_{CL}(x)} + \alpha_{AEM} \frac{RT}{F} \ln \frac{\gamma_{H}^{CH}(x)C_{CH}(x)}{\gamma_{H}^{CL}(x)C_{CL}(x)}
\]

... where \( \alpha \) is the permselectivity of the membrane and \( \gamma \) is the activity coefficient [28]. The activity coefficient is a factor used in thermodynamics to account for deviations from the ideal behavior in a mixture of chemical substances, which depends on the mole fraction of the substance in the mixture. The permselectivity is mainly determined by intermolecular forces, which mediate the interaction between molecules. The resistances on the RED system include the resistance due to conductivity in the HC and LC solutions, the resistance in the ion exchange membranes, and the resistance of the electrode. For the repeated RED pairs, the space-dependent area-specific resistance \( R_{a,cell}(x) \) is expressed as [28,29]

\[
R_{a,cell}(x) = N_{cell} \left( \frac{f}{\lambda_m} \left( \frac{\delta_H}{C_{CH}(x)} + \frac{\delta_L}{C_{CL}(x)} \right) + R_{AEM} + R_{CEM} \right) + R_{el}
\]

... where \( \lambda_m \) is the molar conductivity of the electrolyte (NaCl) solu-
... tion, \( \delta_H \) and \( \delta_L \) are the thicknesses of the HC and LC solution compartments, \( f \) is a measure for the increase in electrical resistance due to the negative effects of the spacer, \( R_{AEM} \) and \( R_{CEM} \) are

2. Model development

In the RED process, concentration polarization occurs, which reduces the effective concentration difference across the membrane. For simplicity, the following assumptions are made to model the RED process: (1) The concentration polarization on both the HC side and LC side is ignored. (2) The ions carried by the trans-
... membrane water flux are not included. (3) The diffusion co-
... ficients for the water and ions are constant. (4) The membrane resistance and membrane permeselectivity are treated as constants under different operating conditions. The modeling for the mass transfer characteristics in the RED process is presented in the Appendix.

Fig. 1 shows a schematic of the RED stack, which comprises repeating HC and LC compartments separated by IEMs. For actual application, conditioned on the feasible and modularized installation and maintenance, the stacks are assumed to be equipped in a constrained space with a fixed cross-sectional area (W × L) and height (H), where W and L are the width and length of the RED stacks, respectively. The cell number \( N_{cell} \) of the stack is calculated by

\[
N_{cell} = \left\lfloor \frac{H - \delta_m}{\delta_H + \delta_L + 2\delta_m} \right\rfloor
\]

... where \([\_]\) is the rounding down operation, and \( \delta_m \), \( \delta_H \), and \( \delta_L \) are the membrane thickness, HC compartment thickness, and LC compartment thickness, respectively.

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R_{a,cell}(x) = N_{cell} \left( \frac{f}{\lambda_m} \left( \frac{\delta_H}{C_{CH}(x)} + \frac{\delta_L}{C_{CL}(x)} \right) + R_{AEM} + R_{CEM} \right) + R_{el}
\]

... where \( \lambda_m \) is the molar conductivity of the electrolyte (NaCl) solu-
... tion, \( \delta_H \) and \( \delta_L \) are the thicknesses of the HC and LC solution compartments, \( f \) is a measure for the increase in electrical resistance due to the negative effects of the spacer, \( R_{AEM} \) and \( R_{CEM} \) are
the membrane area resistances, and \( R_{\text{ci}} \) is the membrane area ohmic resistance of the electrodes and their compartments. There are \( N_{\text{cell}} \) pairs of channels; therefore, the resistance due to conductivity in the HC and LC solutions and that in the ion exchange membranes are multiplied by \( N_{\text{cell}} \). For simplicity, the membrane resistance is treated as a constant under different operating conditions. The solution resistance strongly depends on the solution concentration based on Eq. (3). The effects of operating parameters on RED performance are equivalent to those of the operating parameters on concentration distributions of the RED process, which determine the process conductivity and resistance, and consequently, the power output.

For maximum power of the RED cell, the external load takes the value of the internal resistance. Therefore, the total maximum power output is

\[
P_{\text{max}} = W \int_0^L \frac{1}{8} \frac{E_{\text{cell}}(x)^2}{R_{\text{g,cell}}(x)} \, dx
\]

Due to the flow characteristics in the microchannel, the pump consumption cannot be ignored, and is calculated as \([30,31]\)

\[
P_{\text{pum}} = \int_0^L N_{\text{cell}} \eta_1 L \left( \frac{6\mu H}{W_0 H} + \frac{6\mu L}{W_0 L} \right) \, dx
\]

where \( \eta_1 \) is a correlation factor concerning the geometric effects.

The net power output is \( P_{\text{RED}} = P_{\text{max}} - P_{\text{pum}} \); with the efficiency of the RED stack defined as

\[
\eta_{\text{RED}} = P_{\text{RED}} / \Delta G_{\text{RED}}
\]

where \( \Delta G_{\text{RED}} \) is the maximum potential that can be transformed into electricity in the RED stack, which can be expressed as \([32]\)

\[
\Delta G_{\text{RED}} = 2RT \left[ \left( V_H \frac{C_H}{C_T} \right) L_H + \left( V_L \frac{C_L}{C_T} \right) L_L \right]
\]

where \( C_T \) is the concentration of the mixed concentrated and diluted solutions.

3. Results and discussion

3.1. Model validation

The model presented in this paper is validated by the measured values of a small Qianqiu homogen stack of 25 cells \([29]\) and a Fumasep FAD/FKD stack of 50 cells \([33]\). The specifications of the membrane properties are taken from Refs. \([34,35]\). The detailed membrane parameters are listed in Table 1. The obstruction factor describing the extra electrical resistance of the water compartments due to the influence of the spacer is 1.72 for the Fumasep FAD/FKD stack and 1.6 for the Qianqiu homogen stack. The spacer thickness is \( d_{H} = d_{L} = 2 \times 10^{-4} m \). The input NaCl concentration is 512.8 mol/m\(^3\) for the HC compartment and 17.1 mol/m\(^3\) for the LC compartment. Our proposed model can be validated by the good agreement between the calculation results and experimentally measured data, as shown in Fig. 2.

3.2. Sensitivity analysis

To give the first impression of the behavior with different HC and LC channel thicknesses in a RED cell, the power output and energy efficiency of a 0.1 m \( \times \) 0.1 m RED stack, equipped with Fumasep FAD/FKD, is presented here. The geometrical parameters are listed in Table 2. The membrane properties are based on Ref. \([34,35]\). The input volume flow rate is 500 mL/min, with the NaCl concentration being 512.8 mol/m\(^3\) for the HC compartment and 17.1 mol/m\(^3\) for the LC compartment. The spacer thickness (for both HC and LC compartments) ranges from 9 \( \times \) 10\(^{-5}\) m to 3 \( \times \) 10\(^{-4}\) m. Fig. 3 shows the gross power, net power, and hydrodynamic loss of the Fumasep RED stack as a function of the HC and LC channel thicknesses. For a given stack size, a smaller thickness leads to an increased number of cells for the RED stack, which increases the internal resistance and stack voltage. At larger thicknesses, due to a relatively small stack voltage, the gross power output decreases. According to Eq. (5), a smaller HC/LC thickness leads to a larger hydrodynamic loss, which increases dramatically as the HC/LC thickness decreases. As the net power is the difference between the gross power and the hydrodynamic loss, there exist optimal HC and LC thicknesses, leading to the maximum net power output, as illustrated in Fig. 3.

<table>
<thead>
<tr>
<th>Membrane</th>
<th>( d_{\text{in}} ) (( \mu \text{m} ))</th>
<th>( R(L \text{ \Omega \cdot cm}^{-2}) )</th>
<th>( \alpha ) (%)</th>
<th>( D_{\text{max}} ) (m(^2)/s)</th>
<th>( D_{\text{water}} ) (m(^2)/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qianqiu homogen</td>
<td>250</td>
<td>2.85</td>
<td>1.37</td>
<td>0.863</td>
<td>3.2E-11</td>
</tr>
<tr>
<td>Fumasep FAD/FKD</td>
<td>80</td>
<td>0.89</td>
<td>0.89</td>
<td>0.86</td>
<td>1.3E-11</td>
</tr>
<tr>
<td>Neosepta AMX/CMX</td>
<td>150</td>
<td>2.35</td>
<td>2.91</td>
<td>0.907</td>
<td>5.5E-11</td>
</tr>
<tr>
<td>Selemion AMV/CMV</td>
<td>120</td>
<td>3.15</td>
<td>2.29</td>
<td>0.873</td>
<td>3.1E-12</td>
</tr>
</tbody>
</table>

Fig. 2. Validation of the model. Calculated (line) and measured (square points) power densities of small Qianqiu homogen of 25 cells (a) and Fumasep FAD/FKD of 50 cells (b) as a function of the volume flow rate. The spacer thickness (both compartments) for the RED stack with Fumasep FAD/FKD and Qianqiu homogen is \( d_{H} = d_{L} = 200 \mu\text{m} \). The input NaCl concentrations are 512.8 mol/m\(^3\) for the HC compartment and 17.1 mol/m\(^3\) for the LC compartment, respectively. The input volume flow rates of the HC and LC compartments are equal.
Table 2

<table>
<thead>
<tr>
<th>Input parameters</th>
<th>Symbols</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (K)</td>
<td>T</td>
<td>298</td>
</tr>
<tr>
<td>Module height (m)</td>
<td>H</td>
<td>0.04</td>
</tr>
<tr>
<td>Module width (m)</td>
<td>W</td>
<td>0.1</td>
</tr>
<tr>
<td>Module length (m)</td>
<td>L</td>
<td>0.1</td>
</tr>
<tr>
<td>High concentration (mol/m3)</td>
<td>CH</td>
<td>512.8</td>
</tr>
<tr>
<td>Low concentration (mol/m3)</td>
<td>CL</td>
<td>17.1</td>
</tr>
<tr>
<td>Obstruction factor</td>
<td>f</td>
<td>1.96</td>
</tr>
</tbody>
</table>

Fig. 3. Gross power, net power, and hydrodynamic loss of the Fumasep RED stack as a function of the HC and LC channel thicknesses.

Fig. 4. Energy efficiency of the Fumasep RED stack as a function of the HC and LC channel thicknesses.

The optimization under particle swarm optimization (PSO) [40] for different optimization conditions (optimizing the channel thicknesses of the HC and LC compartments and optimizing both the channel thicknesses and flow rates) is conducted and compared. As shown in Fig. 5, the optimal net power outputs under different optimization methods do not exhibit obvious difference. Therefore, the GA method is suitable for optimizing the present RED system. The parameter settings for the GA and PSO solvers are listed in the Appendix.

4. Optimization

As mentioned above, there exist optimal HC and LC compartment thicknesses, leading to the maximum net power output. Due to the nonlinearity of the system, the optimal values cannot be calculated analytically. The GA method offers a solution to obtain the optimal values of the nonlinear problems, based on the evolution algorithm, which has been extensively adopted in optimizing real thermodynamic systems [36–39]. Here the GA method is employed to obtain the optimal parameters with the maximum net power output as the objective. Furthermore, based on the previous literature, different volume flow rates of the HC and LC compartments can reduce the pumping loss, thus achieving a higher net power [18]. Therefore, for comparison and systematics, an optimization with HC and LC channel thicknesses and volume flow rates being the variables to be optimized is also conducted under the maximum net power output. To justify whether the GA method is suitable for optimizing the present RED system, performance optimization under particle swarm optimization (PSO) [40] for different optimization conditions (optimizing the channel thicknesses of the HC and LC compartments and optimizing both the channel thicknesses and flow rates) is conducted and compared. As shown in Fig. 5, the optimal net power outputs under different optimization methods do not exhibit obvious difference. Therefore, the GA method is suitable for optimizing the present RED system. The parameter settings for the GA and PSO solvers are listed in the Appendix.

4.1. Optimizing the channel thickness of the HC and LC compartments

Based on the GA method, an optimization is conducted for the RED system with a given size (0.1m × 0.1m × 0.05m) to obtain the optimal HC and LC channel thicknesses under the maximum net power output with identical HC and LC flow rates (500 mL/min). A complete flowchart for the optimization and modeling process is illustrated in Fig. 6, the input parameters are listed in Table 2, and the convergence of the optimization can be observed in Fig. 7.

The optimal profiles for flow rate and concentration of the HC and LC compartments under the maximum net power condition for different membranes are depicted in Fig. 8. As the variation in flow rate along the flow direction is considered, both the HC solution flow rate and LC concentration increase along the flow direction, while the LC solution flow rate and HC concentration decrease due to the transmembrane ions and water flux. We can see that under the optimal condition, the channel flow rates for the RED stack with Fumasep FAD/FKD are the smallest. Conditioned on the limited membrane area, more ions can permeate through the IEMs.
Therefore, the outlet concentrations are closer to the mixed one. Due to a relatively small change in the flow rates of the HC and LC solutions, the hydrodynamic loss nearly stays unchanged in the flow direction, which can also be observed in Fig. 9. The gross power density first increases, reaches its maximum value, and then decreases along the flow direction. Near the inlet region, although the Nernst potential is the highest and Ohmic resistance is the highest due to the lowest concentration of the LC compartment, the gross power density is not the highest. In the development of the RED process, the decrease in the magnitude of the Nernst potential is lower than that in the Ohmic resistance. Therefore, the gross power density increases. As the RED process develops further, the Nernst potential decreases much sharply due to a decrease in the NaCl concentration of the HC solution and increase in that of the LC solution. Hence, the gross power density decreases.

The optimal HC and LC compartment thicknesses and the corresponding power output, power density, and cell numbers under the maximum net power output with identical HC and LC flow rates for different membranes are presented in Fig. 10. The RED stack with Fumasep FAD/FKD presents the largest net power output and energy efficiency due to the fixed inlet volume flow rates of the HC and LC solutions. The smallest value of the net power output occurs in the RED stack with Qianqiu heterogen. As shown in Fig. 10(c), the optimal thickness of the HC channel is always larger than that of the LC channel for different membranes. Under the optimal conditions, the RED stack with Fumasep FAD/FKD has the smallest HC and LC compartment thicknesses. Hence, under the constrained size, the cell number of the RED stack with Fumasep FAD/FKD, as well as the total membrane area, is the largest, as shown in Fig. 10(b). Moreover, the net power density of the RED stack with Fumasep FAD/FKD is the largest, while that with Qianqiu homogeneity is the smallest.
4.2. Optimizing both channel thicknesses and flow rates

In the previous part of this section, we optimized the thicknesses of the HC and LC compartments with identical inlet HC and LC volume flow rates. Actually, the non-equal flow rates can lead to a larger net power output, according to our previous study [27]. In what follows, the maximum net power output under the optimal HC and LC channel thicknesses, along with the volume flow rates, is investigated based on the GA method. The other parameters are the same as those in Section 4.1. A complete flowchart of the optimization and modeling process is presented in Fig. 11, and the convergence of the optimization is presented in Figs. 12 and 13.

The optimal HC and LC compartment thicknesses and volume flow rates, as well as the corresponding power output, power density, and cell numbers under the maximum net power output for different membranes, are presented in Fig. 14. Unlike the trends under the maximum net power output with identical inlet volume flow rates, where the optimal thickness of the HC channel is slightly
larger than that of the LC channel, in this section, the optimal thickness of the LC compartment is larger than that of the HC compartment for Fumasep FAD/FKD, Selemion AMV/CMV, and Neosepta AMX/CMX, while the optimal flow rate of the LC compartment is obviously larger than that of the HC compartment. The channel thicknesses of Fumasep FAD/FKD are the smallest, and therefore, the cell number is the largest. The RED stack with Fumasep FAD/FKD, as well as the hydrodynamic loss induced by the largest optimal volume flow rates, thus inducing less Gibbs free energy inputted to achieve a higher energy efficiency.

The optimal profiles for the flow rate and concentration of the HC and LC compartments under the maximum net power output for different membranes are presented in Fig. 15. Both the HC solution flow rate and LC concentration increase along the flow direction, while the LC solution flow rate and HC concentration decrease due to the transmembrane ions and water flux. Under the optimal conditions, the flow rate of the HC solution is less than that of the LC solution. Fig. 16 depicts the optimal profiles for power density and hydrodynamic loss under the maximum net power output for different membranes. The power density first increases, reaches the maximum value, and then decreases along the flow direction for the RED stack with Fumasep FAD/FKD. The net power density presents the same trend with the gross power density because the hydrodynamic loss nearly stays stable along the flow direction.

Along the flow direction, in the inlet region, the optimal profile of the gross power density obtained in Section 4.1 is higher than that obtained in this section. In contrast, in the outlet region, the optimal profile of the gross power density is much less, resulting in the average net power density obtained in this section being more than that obtained in Section 4.1, as shown in Fig. 17. As depicted in

FIG. 13. Values of the inlet volume flow rates of high concentration and low concentration solutions in the final populations for optimization in Sec. 4.2.

FIG. 14. Optimal HC and LC compartment thickness and volume flow rates, and the corresponding power output, power density and cell numbers under the maximum net power output for different membranes.

FIG. 15. Optimal profiles for flow rate and concentration along the flow direction under the maximum net power output for different membranes.

FIG. 16. Optimal profile of power density and hydrodynamic loss along the flow direction under the maximum net power output for different membranes.
the compartment thickness and volume. For Qianqiu homogen, the net power output is increased by decreased. As the power output is increased, so is the energy efficiency. To further, the optimal channel thickness and volume flow rate of the HC and LC compartments are also investigated under the maximum net power output. For most of the studied membranes, the optimal channel thickness and volume flow rate of the HC compartment are, respectively, much less than those of the LC compartment. Compared to the performance optimized by the channel thickness, the performance of the RED systems optimized by both volume flow rate and compartment thickness is much improved. For Qianqiu homogen, the net power output is increased by 70.86% and the energy efficiency is increased by 313.91%. Therefore, the compartment thickness and volume flow rate of the LC and HC solutions should be addressed simultaneously for designing and operating actual RED stacks.

Furthermore, in the present analysis, due to the space constraints, the cell number of the RED stack differs with different membranes, whose cost is not considered here. As to offer a more practical guidance on the design and operation of the RED stack, the economic analysis should be conducted further.

Acknowledgments

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Appendix

A1. Modeling the mass transfer characteristics in the RED process

According to our previous study, the control equations illustrating the transmembrane characteristics in the RED process are given by

\[
\frac{d[V_H(x)\rho_H(x)]}{dx} = -W_{J_{NaCl}(x)}M_{NaCl} + W_{J_{water}(x)}M_{H_2O} \tag{A1}
\]

\[
\frac{d[V_L(x)\rho_L(x)]}{dx} = W_{J_{NaCl}(x)}M_{NaCl} - W_{J_{water}(x)}M_{H_2O} \tag{A2}
\]

\[
\frac{d[V_H(x)\Delta H(x)]}{dx} = -W_{J_{NaCl}(x)} \tag{A3}
\]

\[
\frac{d[V_L(x)\Delta L(x)]}{dx} = W_{J_{NaCl}(x)} \tag{A4}
\]

where \(\rho\) is the density of the NaCl aqueous solution impacted by the concentration \([41]\), \(J_{NaCl}(x)\) denotes salt transport from the HC electrolyte to LC electrolyte originating from Columbic force and co-ion transport, and \(J_{water}\) represents the water flux due to osmosis of water from the LC solution to the HC solution compartment.
\[ J_F(x) = \frac{t_i E_{cell}(x)}{2R_{a,cell}(x)F} + \frac{2D_i}{\delta_m} [C_R(x) - C_L(x)] \]  
(A5)

\[ J_{water}(x) = -\frac{2D_{water}}{\delta_m} [C_R(x) - C_L(x)] \]  
(A6)

Eqs. (A1) and (A2) indicate the mass conservation of the HC and LC solutions, and Eqs. (A3) and (A4) indicate the ion conservations of \( \text{Na}^+ \) and \( \text{Cl}^- \) in the HC and LC solutions, respectively. The distributions of the volume flow rate and concentration along the flow direction can be evaluated by solving the governing mass and species transfer in Eqs. (8)–(11), with the boundary conditions given by

\[ C_R(0) = C_{R,in}, V_R(0) = V_{R,in} \]  
(A7)

\[ C_L(0) = C_{L,in}, V_L(0) = V_{L,in} \]  
(A8)

### A2. Parameter settings for the GA and PSO solvers

The optimization (GA and PSO) is based on the GA and PSO tools implemented in the MATLAB software. In the GA optimization method, the population size is 200, the number of generations is 50, the crossover ratio is 0.8, and the mutation ratio is 0.2. In the PSO optimization method, the number of particles in the swarm is 300. The other parameter settings use the default values in the GA and PSO tools implemented in the MATLAB software.

### Nomenclature

- **A**: Effective hydrated ion radius (pm)
- **C**: Electrolyte concentration (molality) (mol ⋅ kg\(^{-1}\))
- **D\(_{\text{NaCl}}\)-D\(_{\text{Water}}\)**: Diffusion constants of NaCl and water, respectively (m\(^2\) ⋅ s\(^{-1}\))
- **\(E_{cell}\)**: Electromotive force of one cell (V)
- **F**: Faraday constant (96485 C ⋅ mol\(^{-1}\))
- **f**: Obstruction factor
- **\(\Delta G\)**: Maximum potential that can be transformed into electricity in the RED stack (W)
- **\(J\)**: Molar flux (mol ⋅ s\(^{-1}\) ⋅ m\(^{-2}\))
- **\(J_d\)**: Current density (A/m\(^2\))
- **\(M_{H_2O}\)**: Mole mass H\(_2\)O (0.01802 kg ⋅ mol\(^{-1}\))
- **\(N\)**: Cell number
- **\(P\)**: Power (W)
- **\(P_d\)**: Power density (W/m\(^2\))
- **\(R\)**: Gas constant (8.314 J ⋅ mol\(^{-1}\) ⋅ K\(^{-1}\))
- **\(R_{\text{AEM}}-R_{\text{CEM}}\)**: Electrode area ohmic resistance (Ω ⋅ m\(^2\))
- **\(R_{\text{electrode}}\)**: Area resistance of the AEM and CEM, respectively (Ω ⋅ m\(^2\))
- **\(T\)**: Temperature (K)
- **\(V\)**: Volume flow rate (m\(^3\) ⋅ s\(^{-1}\))
- **\(W, L\)**: Width and length of the RED stack (m)
- **\(x\)**: Axial position along the RED module (m)
- **\(z\)**: Valency

### Greek symbols

- **\(\alpha\)**: Permeselectivity of the ion-selective membrane
- **\(\gamma\)**: Activity coefficient
- **\(\mu\)**: Viscosity (kg ⋅ m\(^{-1}\) ⋅ s\(^{-1}\))
- **\(\delta_m\)**: Membrane thickness (m)
- **\(\delta_{H, L}\)**: Thickness of the HC and LC solution compartment, respectively (m)

### Subscripts

- **H**: High concentration
- **L**: Low concentration
- **max**: Maximum

### Abbreviations

- **HC**: High concentration
- **LC**: Low concentration
- **RED**: Reversed electrodialysis
- **PRO**: Pressure retarded osmosis
- **CEM**: Cation-exchange membrane
- **AEM**: Anion-exchange membrane

### References


