Salinity gradient power: Influences of temperature and nanopore size

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Salinity gradient power: Influences of temperature and nanopore size
Shiojenn Tseng,¹ Yu-Ming Li,² Chih-Yuan Lin,² Jyh-Ping Hsu²*

Abstract

Salinity gradient power is a promising, challenging, and readily available renewable energy. Among various methods for harvesting this clean energy, nanofluidic reverse electrodialysis (NRED) is of great potential. Since ionic transport depends highly on the temperature, so is the efficiency of the associated power generated. Here, we conduct a theoretical analysis on the influences of temperature and nanopore size on NRED, focusing on temperature and nanopore size. Results gathered reveal that the maximum power increases with increasing temperature, but the conversion efficiency dependents weakly on temperature. In general, the smaller the nanopore radius or the longer the nanopore the better the ion selectivity is. These results provide desirable and necessary information for improving the performance of NRED as well as designing relevant units in renewable energy plants.

Keywords: salinity gradient power; reverse electrodialysis; temperature effect; size effect

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1. Introduction

Among the potential resources for renewable energy such as sunlight,\(^1\) wind, tide, waves, and geothermal heat,\(^2\) salinity gradient,\(^3-9\) which generates electrical energy by transferring Gibbs free energy of mixing through nanofluidic reverse electrodialysis (NRED), the main component of which is of nanoscale, is of particular interest. Salinity gradient can be accomplished through connecting two relatively large reservoirs containing different salt concentrations by a nanopore. The salt gradient established drives ions from the high salt concentration reservoir to the low salt concentration reservoir. In particular, if the nanopore is positively (negatively) charged (i.e., ion-selective nanopore), it facilitates transferring of anions (cations) from one reservoir to the other. Adopting an abiotic single-pore nanofluidic energy-harvesting system, Guo \textit{et al}.\(^{10}\) demonstrated that the Gibbs free energy associated with a salinity gradient can be efficiently converted into electricity. Kim \textit{et al}.\(^{11}\) showed that in the case of a silica nanopore and an aqueous KCl solution, the highest retrievable power density is 7.7 W/m\(^2\). Cao \textit{et al}.\(^{12}\) reported that the highest power is ca. 45 pW for the case of a polyimide nanopore and an aqueous KCl solution, and ca. 22 pW for the case of an aqueous NaCl solution. Kim \textit{et al}.\(^{13}\) found that the highest harvestable power from a NRED with anodic alumina nanopores and aqueous NaCl solution is 542 nW, which is higher than that from other NRED devices. Varying the concentration difference, the pore size of a polycarbonate track-etch (PCTE) membrane, and the types of salt solution, Kwon \textit{et al}.\(^{14}\) examined the performance of a portable NRED
device. They showed that the electricity generated by monovalent ions is larger than that by bivalent ions. In addition, for the nominal diameter ranging from 15 to 100 nm, the performance of a NRED cell can be enhanced by reducing its pore size. Gao et al.\textsuperscript{15} proposed using an ionic diode membrane to harvest electric energy from a salinity gradient. They claimed that the power density can be up to 3.46 W/m\textsuperscript{2}, exceeding appreciably several commercial ion-exchange membranes.

In addition to experimental efforts, several theoretical attempts have also been made in modeling salinity gradient. For instance, Yeh et al.\textsuperscript{16} examined the influence of the direction of salt gradient on the efficiency of a NRED device with a cone-shaped nanopore. They showed that a nanopore with its base end having a higher salt concentration has a larger energy conversion efficiency than that for the case where its tip end has a higher salt concentration. This observation was attributed to the overlapping of the electrical double layer (EDL) near the tip end of a nanopore. Jeong et al.\textsuperscript{17} studied numerically the ionic transport in the cell pair of a NRED device. Kang et al.\textsuperscript{18} studied theoretically the effect of nanopore size on its performance in a NRED device. It was found that the smaller the nanopore radius and/or the higher the salt concentration on the high salt concentration side of the nanopore the larger the power per unit nanopore cross section area. Several other interesting results were also observed, but the rationale behind them was not discussed in detail. For instance, the curves of (power/nanopore cross section area) against nanopore
length for various levels of the salt concentration on the low salt concentration side of the
nanopore intersect with each other. In addition, the ratio of (power/nanopore cross section
area) can have a local maximum as the nanopore length varies.

Among various factors that might affect the performance of a NRED device,
temperature and nanopore size are particularly significant. The influence of the latter is
obvious, and that of the former is because almost all the physicochemical properties, such
as ionic mobility, permittivity, and viscosity, are temperature dependent. Taghipoor et al.,19
for example, concluded that the electrical conductance of a nanochannel can be influenced
significantly by temperature. The translocation of biomolecules through a nanopore is also
affected by temperature.20,21 In fact, several temperature-responsive nanostructural devices
have been designed to regulate ionic transport.22-25 Although various factors have been
examined for their influence on the performance of a NRED device, the influence of
temperature is seldom discussed. Considering the great potential of harvesting energy by
NRED, a detailed understanding of its performance under various conditions is highly
desirable and necessary. In this study, attempts are made to assess the performance of a
NRED device, focusing on the influences of temperature and nanopore size.

2. Theory

As illustrated in Fig. 1, we consider a cylindrical nanopore of length $L_n$ and radius $R_n$
connecting two same, large cylindrical reservoirs of radius $R_r$ and length $L_r$. The wall of the
Fig. 1. Transport of ionic species through a cylindrical nanopore of length $L_n$ and radius $R_n$ connecting two same, large cylindrical reservoirs of radius $R_r$ and length $L_r$. $\Omega_n$, $\Omega_r$ and $\Omega_s$ are the nanopore wall, the reservoir wall, and the reservoir surface, respectively.

The nanopore is charged and that of the reservoirs is free of charge. The bulk salt concentration in the left (right) reservoir is $C_H (C_L)$ with $C_H > C_L$. The cylindrical coordinates are adopted with the origin at the center of the left surface of the left reservoir.

### 2.1 Governing equations

The present problem can be described by the set of equations below:

\[
\nabla^2 \phi = -\frac{1}{\varepsilon_r \varepsilon_0} \sum_{i=1}^{N} z_i FC_i \\
J_i = C_i \mathbf{u} - \mathbf{D}_i \left( \nabla C_i + \frac{z_i FC_i}{RT} \nabla \phi \right) \\
\nabla \cdot \mathbf{J}_i = 0 \\
\nabla \cdot \mathbf{u} = 0 \\
\mu \nabla^2 \mathbf{u} - \nabla p - \rho_f \nabla \phi = 0
\]

$\phi$, $e$, $\varepsilon_r$, $\varepsilon_0$, $\mathbf{u}$, $F$, $R$, $T$, $\mu$, $p$, $\rho_f$, and $N$ are the electric potential, the elementary charge, the
relative permittivity, the permittivity of a vacuum, the fluid velocity, Faraday constant, gas constant, the absolute temperature, the fluid viscosity, the pressure, the space charge density, and the number of ionic species, respectively. $z_i$, $C_i$, $J_i$, and $D_i$ are the valence, the concentration, the flux, and the diffusivity of the $i$th ionic species. Note that $\varepsilon_i$, $D_i$, and $\mu_i$ are all temperature dependent. For illustration, we consider an aqueous NaCl solution (i.e., $N=2$) and, for simplicity, we assume its physical properties are essentially the same as those of water. Therefore, the temperature dependence of $\varepsilon_i$ is\textsuperscript{26,27}

$$\varepsilon_i = \exp[4.47615 - 4.60128 \times 10^{-3} (\delta T) + 2.6952 \times 10^{-7} (\delta T)^2]$$  
(6)

where $\delta T = T - 273.15$, $0 \leq \delta T \leq 100$.

The temperature dependence of $\mu_i$ is\textsuperscript{28}

$$\mu = 2.414 \times 10^{-5} \times 10^{247.8/(T - 140)}, \quad 273.15 \leq T \leq 643.15$$  
(7)

The Nernst-Haskell equation\textsuperscript{29,30} is adopted for the temperature dependence of $D_i$:

$$D_i = \frac{RT}{F^2} \left[ \frac{1/z_i}{1/\lambda_i^0} \right]$$  
(8)

$\lambda_i^0$ is the limiting conductance of the $i$th ionic species.

The temperature dependence of $\lambda_i^0$ is\textsuperscript{31}

$$\lambda_i^0 = \lambda_i^0(298.15) + a(\delta T) + b(\delta T)^2 + c(\delta T)^3,$$  
(9)

where $\lambda_i^0(298.15)$ is the limiting conductance of the $i$th ionic species at 298.15 K, $\delta T = T - 298.15$, $-20 \leq \delta T \leq 30$. The values of $a$, $b$, and $c$ for Na$^+$ and Cl$^-$ are listed in Table 1.\textsuperscript{31}
Table 1. Values of the parameters used in eqn (9)

<table>
<thead>
<tr>
<th></th>
<th>( \lambda_i^0 ) (298.15 K)</th>
<th>( a )</th>
<th>( b \times 10^2 )</th>
<th>( c \times 10^4 )</th>
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<td>Na(^+)</td>
<td>50.15</td>
<td>1.09160</td>
<td>0.47150</td>
<td>-0.1150</td>
</tr>
<tr>
<td>Cl(^-)</td>
<td>76.35</td>
<td>1.54037</td>
<td>0.46500</td>
<td>-0.1285</td>
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2.2 Boundary conditions

The system under consideration is symmetric about the nanopore axis, and no pressure gradient is applied across the reservoirs. In addition, we assume the following: (i) The nanopore wall is maintained at a constant charge density \( \sigma = \sigma_n \), and the reservoir wall is free of charge \( (\sigma = 0) \). (ii) The wall of nanopore \( \Omega_n \) and that of reservoir \( \Omega_r \) are impermeable to ions. (iii) \( \Omega_n \) is non-slip and \( \Omega_r \) is slip. Therefore, the following boundary conditions apply:

\[
\begin{align*}
-\varepsilon \varepsilon_0 \frac{\partial \phi}{\partial n} &= \sigma_n \quad \text{on} \quad \Omega_n, \\
-\varepsilon \varepsilon_0 \frac{\partial \phi}{\partial n} &= 0 \quad \text{on} \quad \Omega_r, \\
n \cdot J_i &= 0 \quad \text{on} \quad \Omega_n \quad \text{and} \quad \Omega_r.
\end{align*}
\]

\( n \) is the unit outer normal vector, and \( \partial / \partial n \) denotes the variation along \( n \). In addition, we assume that \( \phi = 0 \) and \( \Omega_3 \) is free of viscous stress.

The electric current \( I \) can be evaluated by

\[
I = \int_A \sum_{i=1}^N z_i e (n \cdot J_i) dA,
\]

where \( A \) denotes either end of the reservoirs. The selectivity of the nanopore is measured by the transference number \( t_+ \)

\[
t_+ = \frac{I_+}{I_+ + |I_-|}
\]
$I_+ \text{ and } I_- \text{ are the electric currents contributed by cations and anions, respectively, } t_+ \text{ ranges from 0 to 1. If } 0.5 < t_+ < 1, \text{ the nanopore is cation selective; otherwise, it is anion selective. If } t_+ = 0.5, \text{ the nanopore is not ion selective. In our case, if } 0.5 < t_+ < 1, \text{ a nanopore facilitates the transport of Na}^+ \text{ from the left reservoir (high salt concentration) to the right reservoir (low salt concentration), so that Na}^+ (\text{Cl}^-) \text{ accumulates in the right (left) reservoir. This induces a diffusion potential } E_{\text{diff}}^{32}$

\[
E_{\text{diff}} = (2t_+ - 1)\frac{RT}{zF}\ln \left( \frac{\gamma_H C_H}{\gamma_L C_L} \right) \tag{15}
\]

$\gamma_H \text{ and } \gamma_L \text{ are the activity coefficients of the bulk concentrations in left and right reservoirs, respectively. According to Bromley,}^{33}$

\[
\log \left( \frac{\gamma_{H(L)}^{\frac{1}{z_z^+}}}{\gamma_{H(L)}^{\frac{1}{z_z^-}}} \right) = \frac{-0.511I_s^{\frac{1}{2}}}{1 + I_s^{\frac{1}{2}}} + \left( \frac{0.06 + 0.03444}{\rho_w} \right)I_s + 0.0574I_s \left( \frac{z_+ z_-}{z_+ z_-} \rho_w \right) \tag{16}
\]

$z_+, z_-, I_+, \text{ and } \rho_w \text{ are the valences of cations and anions, the ionic strength, and the density of water,}^{34} \text{ respectively. Note that } E_{\text{diff}} \text{ retards the transfer of Na}^+ \text{ from the left reservoir to the right reservoir.}$

If we let $\Omega$ be the internal resistance of the nanopore, the electric potential difference of the system under consideration, $\Delta V$, is

\[
\Delta V = E_{\text{diff}} - I\Omega \tag{17}
\]

The harvestable electric power is the product of the ionic current and the potential, and since the maximum electric power $P_{\text{max}}$ occurs when the electric potential is half the
diffusion potential,

\[ P_{\text{max}} = \frac{IE_{\text{diff}}}{2} \]  

(18)

The corresponding energy conversion efficiency \( \eta \) is defined as the ratio of the retrievable electric power to the Gibbs free energy of mixing\(^{35}\)

\[ \eta = \frac{I \Delta V}{(J_+ + J_-)RT \ln \left( \frac{y_H C_H}{y_L C_L} \right)} \]  

(19)

\( J_+ \) and \( J_- \) are the fluxes of cations and anions, respectively. The efficiency corresponding to the maximum power generation, \( \eta_{\text{max}} \), is

\[ \eta_{\text{max}} = \frac{(2t_+ - 1)^2}{2} \]  

(20)

Note that \( \eta_{\text{max}} \) depends on \( t_+ \) only.

The present problem is solved by COMSOL (version 4.3a, www.comsol.com) operating in a high performance cluster. Its applicability has been verified previously.\(^{36,37}\) Typically, the number of meshes elements used is ca. 90000. The behavior of the system under consideration is examined by numerical simulation through varying the nanopore length \( L_n \), its radius \( R_n \), and the absolute temperature \( T \). For illustration, we assume \( L_n = 500 \) nm, \( R_n = 500 \) nm, and \( \sigma_n = -0.5 \, e/\text{nm}^2 \).\(^{10,38,39}\) In addition, \( C_L \) is fixed at 1 mM, and \( C_H \) varies from 10 to 1000 mM.

3. Results and Discussion

Fig. 2 summarizes the dependence of the electric current \( I \) on the concentration
Fig. 2. Variation of the electrical current $I$ with the concentration ratio ($C_H/C_L$) for various combinations of $R_n$ and $L_n$ at three values of temperature (red curve: 308.15 K; black: 298.15 K; blue: 288.15 K) for $R_n=8$ nm and $L_n=300$ nm, (a), $R_n=20$ nm and $L_n=300$ nm, (b), $R_n=8$ nm and $L_n=1000$ nm, (c), and $R_n=20$ nm and $L_n=1000$ nm, (d).

ratio ($C_H/C_L$) for various combinations of $R_n$ and $L_n$ at three representative levels of temperature.

Fig. 2(a) reveals that the electric current $I$ increases monotonically with increasing temperature. As can be seen in Fig. 3, this results from the increase in the ionic diffusivities with temperature.

Fig. 2(a) shows that at $R_n=8$ nm and $L_n=300$ nm, $I$ increases monotonically with
increasing \( (C_H/C_L) \). However, it is interesting to see in Fig. 2(b) that at \( R_n=20 \text{ nm} \) and \( L_n=300 \text{ nm} \), \( I \) has a local maximum as \( (C_H/C_L) \) varies. This is because as \( (C_H/C_L) \) increases, although the amount of counterions (Na\(^+\)) available for ionic transport through the nanopore increases, the electric double layer\(^{40-41} \) is thinner at the same time. If the nanopore radius gets larger, EDL overlapping becomes less significant, thereby facilitating the transport of coions (Cl\(^-\)), so that the net electric current decreases. This is exemplified in Fig. 4 that for each level of \( (C_H/C_L) \), the concentration of Cl\(^-\) at \( R_n=20 \text{ nm} \) is higher than that at \( R_n=8 \text{ nm} \), and the concentration of Cl\(^-\) approaches that of Na\(^+\) as \( (C_H/C_L) \) increases, yielding the local maximum in Fig. 2(b). If \( L_n \) is raised to 1000 nm, it becomes difficult for both counterions and coions to diffuse through the nanopore, especially for the later. Consequently, the concentration of Cl\(^-\) near the right-hand side of the nanopore at \( L_n=1000 \)
Fig. 4. Axial variation in the cross sectional averaged ionic concentration for $T=298.15$ K at $R_n=8$ nm and $L_n=300$ nm, (a), $R_n=20$ nm and $L_n=300$ nm, (b), $R_n=8$ nm and $L_n=1000$ nm, (c), $R_n=20$ nm and $L_n=1000$ nm, (d). Solid (dotted) curve: $\text{Na}^+$ ($\text{Cl}^-$). Black curve: $C_{\text{H}}/C_{\text{L}}=800$; red: $C_{\text{H}}/C_{\text{L}}=300$; blue: $C_{\text{H}}/C_{\text{L}}=60$, green curve: $C_{\text{H}}/C_{\text{L}}=20$. The shaded region highlights the nanopore interior.

nm is lower than that at $L_n=300$ nm. In addition, because the rate of decrease in the concentration of $\text{Cl}^-$ is much faster than that of $\text{Na}^+$, $I$ does not show a local maximum in Fig. 2(d).

Fig. 5 summarizes the variations of the transference number $t_+$ and the conversion efficiency $\eta_{\text{max}}$ with $(C_{\text{H}}/C_{\text{L}})$. This figure suggests that the influence of the temperature on $t_+$ is inappreciable, so is that on $\eta_{\text{max}}$. This is because for a fixed value of $(C_{\text{H}}/C_{\text{L}})$, $t_+$ is essentially a function of the ionic diffusivities, and is proportional to $D_+/(D_++D_-)$, which
Fig. 5. Variation of the transference number $t_+$ and the maximum conversion efficiency $\eta_{\text{max}}$ with the concentration ratio ($C_H/C_L$) for various combinations of $R_n$ and $L_n$ at three values of temperature (red curve: 308.15 K; black: 298.15 K; blue: 288.15 K) for $R_n=8$ nm and $L_n=300$ nm, (a), $R_n=20$ nm and $L_n=300$ nm, (b), $R_n=8$ nm and $L_n=1000$ nm, (c), and $R_n=20$ nm and $L_n=1000$ nm, (d). Solid (dotted) curve: variation of $t_+$ ($\eta_{\text{max}}$).

Both $t_+$ and $\eta_{\text{max}}$ decrease with increasing ($C_H/C_L$). This arises from the decrease in the electric double layer thickness with increasing ($C_H/C_L$), as mentioned previously. Therefore, $t_+$ decreases accordingly, and the nanopore becomes less ion selective. Note that the longer the nanopore (larger $L_n$) and/or the narrower the nanopore (smaller $R_n$) the better its selectivity is. This phenomenon is similar to the influence of nanopore size on the electric current. As discussed earlier, the larger the nanopore radius and/or the shorter the nanopore
Fig. 6. Variation of the diffusion potential $E_{\text{diff}}$ with the concentration ratio ($C_H/C_L$) for various combinations of $R_n$ and $L_n$ at three values of temperature (red curve: 308.15 K; black: 298.15 K; blue: 288.15 K) for $R_n=8$ nm and $L_n=300$ nm, (a), $R_n=20$ nm and $L_n=300$ nm, (b), $R_n=8$ nm and $L_n=1000$ nm, (c), and $R_n=20$ nm and $L_n=1000$ nm, (d).

the easier the transfer of Cl$^-$, yielding a smaller selectivity. Therefore, the largest selectivity occurs at $R_n=8$ nm and $L_n=1000$ nm (Fig. 5(c)) and smallest selectivity at $R_n=20$ nm and $L_n=300$ nm (Fig. 5(b)).

According to eqn (15), $E_{\text{diff}}$ varies with $t_*$, $T$, and $\ln(\gamma_H C_H/\gamma_L C_L)$. Since compared with that of $\ln(C_H/C_L)$, the change of $\ln(\gamma_H/\gamma_L)$ is unimportant, we consider the influence of $\ln(C_H/C_L)$ only. As can be seen in Fig. 6, the higher the temperature the larger the $E_{\text{diff}}$, which is expected from eqn (15). All the curves in Fig. 6 show a local maximum as
Fig. 7. Variation of the maximum power per unit cross-sectional nanopore area ($P_{\text{max}}/A$) with the concentration ratio ($C_H/C_L$) for various combinations of $R_n$ and $L_n$ at three values of temperature (red curve: 308.15 K; black: 298.15 K; blue: 288.15 K) for $R_n=8$ nm and $L_n=300$ nm, (a), $R_n=20$ nm and $L_n=300$ nm, (b), $R_n=8$ nm and $L_n=1000$ nm, (c), and $R_n=20$ nm and $L_n=1000$ nm, (d).

$\ln(C_H/C_L)$ varies. This is because although $E_{\text{diff}}$ increases with increasing $\ln(C_H/C_L)$, $t_+$ decreases at the same time, as seen in Fig. 5, leading to a smaller $E_{\text{diff}}$. The former (latter) dominates at small (large) $\ln(C_H/C_L)$, yielding a local maximum in $E_{\text{diff}}$. As mentioned previously, $E_{\text{diff}}$ comes from the asymmetric distributions in Na$^+$ and Cl$^-$, retarding the transfer of Na$^+$. If $t_+$ is large, implying that the amount of Na$^+$ transfer is large and, therefore, a higher $E_{\text{diff}}$ is needed to retard its transfer. The maximal value of $E_{\text{diff}}$ occurs at $R_n=8$ nm and $L_n=1000$ nm (Fig. 6(c)), and the minimal value at $R_n=20$ nm and $L_n=300$ nm.
Fig. 6(b)), which are consistent with the trends of \( t_* \) seen in Fig. 5.

Fig. 7 illustrates the variation of the maximum power per unit cross-sectional nanopore area \( (P_{\text{max}}/A) \) with the concentration ratio \( (C_{H}/C_{L}) \) for various combinations of \( R_n \) and \( L_n \) at three values of temperature. Since both the electric current \( I \) and the diffusion potential \( E_{\text{diff}} \) increase with increasing temperature, the higher the temperature the larger the \( (P_{\text{max}}/A) \). A comparison between the results for \( R_n=8 \) nm and those for \( R_n=20 \) nm reveals that the \( (P_{\text{max}}/A) \) in the latter has a local maximum as \( (C_{H}/C_{L}) \) varies. In addition, the \( (P_{\text{max}}/A) \) at \( R_n=20 \) nm is smaller than that at \( R_n=8 \) nm. This behavior is similar to that of \( E_{\text{diff}} \) in Fig. 6. A comparison between the results for \( L_n=300 \) nm and those for \( L_n=1000 \) nm indicates that the \( (P_{\text{max}}/A) \) in the former is larger than that in the latter. This behavior is similar to that of \( I \) in Fig. 2. Therefore, the largest \( (P_{\text{max}}/A) \) occurs at \( R_n=8 \) nm and \( L_n=300 \) nm (Fig. 6(a)), and smallest \( (P_{\text{max}}/A) \) at \( R_n=20 \) nm and \( L_n=1000 \) nm (Fig. 6(d)).

Conclusions

We modeled theoretically the salinity gradient power based on nanopore/nanochannel reverse electrodialysis (NRED), focusing on the influences of temperature and nanopore size. The results of numerical simulation reveal that these factors are significant in designing a NRED device. For instance, because a larger electric current \( I \) and a higher diffusion potential \( E_{\text{diff}} \) can be achieved at an elevated temperature, a higher maximum power per unit nanopore cross-sectional area \( (P_{\text{max}}/A) \) can be harvested. However, the
transference number of cations \( t^+ \) and the maximum conversion efficiency \( \eta_{\text{max}} \) are influenced only slightly due to that the ionic diffusivities of cations and anions increase with temperature at similar rate. We show that the smaller the nanopore radius \( R_n \) and/or the longer the nanopore length \( L_n \) the better the ion selectivity and, therefore the larger the \( \eta_{\text{max}} \). This arises from the influence of electric double layer (EDL): the degree of EDL overlapping is serious if \( R_n \) is small, and it is difficult for ions, especially coions, to diffuse through the nanopore. It is interesting to observe that the electric current \( I \) has a local maximum as the concentration ratio \( (C_H/C_L)\)=(bulk salt concentration in the high salt concentration reservoir/bulk salt concentration in the low salt concentration reservoir) varies at \( R_n=20 \) nm and \( L_n=300 \) nm, which is attributed to that the transport of coions in this case is easier than that in other cases. Due the competition between \( (C_H/C_L) \) and \( t^+ \), \( E_{\text{diff}} \) shows a local maximum for each combination of \( R_n \) and \( L_n \). For \( (C_H/C_L) \) ranges from 10 to 1000 and \( T \) from 288.15 to 308.15 K, since \( E_{\text{diff}} \) is influenced mainly by \( t^+ \), it has the largest value at \( R_n=8 \) nm and \( L_n=1000 \) nm, occurring at \( (C_H/C_L) \geq 400 \) and \( T \geq 308.15 \) K. In general, more power can be harvested at about the same conversion efficiency with higher temperature. Because \( I(L_n=300 \text{ nm})>I(L_n=1000 \text{ nm}) \), and \( E_{\text{diff}}(R_n=8 \text{ nm})>E_{\text{diff}}(R_n=20 \text{ nm}) \), \( (P_{\text{max}}/A) \) has the largest value at \( L_n=300 \) nm and \( R_n=8 \) nm.

References


2065-2070.


