Model based evaluation of alkaline anion exchange membrane fuel cells with water management

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\textbf{HIGHLIGHT}

- The anion exchange membrane fuel cells with the water transport is numerically studied.
- The cell performance at unbalanced pressure operation is analyzed.
- The anode relative humidity has a crucial impact on the cell performance.
- Thin membrane and unbalanced pressure operation are preferred to facilitate water transport.

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Water management
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\textbf{ABSTRACT}

The aim of this work is to improve alkaline anion exchange membrane fuel cell performance with water management. The mathematical model of alkaline anion exchange membrane fuel cells was developed with consideration of the water transport inside the membrane. The effects of key operating parameters such as the cathode relative humidity, anode relative humidity, cathode pressure, anode pressure on the net water flux across the membrane and the cell performance were analyzed with the unbalanced pressure concept to enhance the water back diffusion from the anode side to the cathode side. The increasing of the anode and cathode relative humidity lead to high water content, enhancement of membrane conductivity and reduction of ohmic loss resulting in a significant improvement of cell performance, especially an increase in the anode relative humidity. The high cell performance can achieve with the unbalanced pressure operation and the use of thin membrane is also preferred to facilitate water back diffusion from the anode to the cathode and enhance the cell performance.

1. Introduction

The increasing energy demand, finite nature of fossil fuel resources and global environmental challenges stimulate the research about alternative energies and clean technologies. The use of available fuels with efficient and environmentally friendly technologies is necessary for long term and sustainable development. A fuel cell is an electrochemical device, producing much less emissions compared to conventional heat engines used in most power plants. Fuel cells convert the chemical energy of fuels to electricity through an electrochemical process and produce only water and heat as by-products. An alkaline fuel cell has been developed since at least 1902 and it was used for the Apollo mission. It provides a high overall electrical efficiency greater than most other fuel cell types \cite{1}. Typically, the liquid alkaline electrolyte (KOH) is used for a conventional alkaline fuel cell. However, it is highly sensitive to CO\textsubscript{2} in the ambient air because hydroxyl ions can react with CO\textsubscript{2} as shown in Eqs. (1) and (2) and these reactions decrease the hydroxyl ions for the electrochemical reaction. Also, the K\textsubscript{2}CO\textsubscript{3} is formed (see Eq. (3)) and precipitates in the porous electrode and then it blocks ion transfer resulting in the reduction of performance of the alkaline electrolyte \cite{2}.

\begin{align*}
\text{OH}^+ + \text{CO}_2 & \rightleftharpoons \text{HCO}_3^- \\
\text{OH}^+ + \text{HCO}_3^- & \rightleftharpoons \text{CO}_2^2^- + \text{H}_2\text{O} \\
\text{CO}_2^2^- + 2\text{K}^+ & \rightleftharpoons \text{K}_2\text{CO}_3
\end{align*}

However, alkaline fuel cells were extensively investigated throughout the 1960s to the 1980s \cite{3}. The emergence of a proton
exchange membrane fuel cell (PEMFC) has subsequently attracted the most of the attention from developers and thus the works focusing on alkaline fuel cells have decreased. However, an alkaline anion exchange membrane fuel cell employing a hydroxide conductive membrane (Solid electrolyte) has been developed and has gained more attention from developers again in recent years. This is primarily because the high cost of PEMFCs remains problematic and the issue of availability of Platinum which is the required catalyst for the anode and the cathode of PEMFCs. With the solid electrolyte of anion exchange membrane fuel cells, electrolyte leakage and corrosion problems are mitigated [4]. Although the electrochemical kinetics of the anode of anion exchange membrane fuel cells are slower than those in acidic conditions [5], the diffusion-limiting currents increase under the alkaline condition and thus hydrogen and hydroxide anions are sufficient to maximize the electrochemical oxidation of hydrogen at the anode [6]. In addition, the non-platinum catalysts can be used for anion exchange membrane fuel cells because of the high pH of the electrolyte. However, the CO₂ in the ambient air can also react with hydroxide anions to form HCO₃⁻ and CO₃²⁻ via the carbonation resulting in lowering of hydroxide conductivity and thus anion exchange membrane fuel cell performance loss, especially at low cell current and high CO₂ concentration [7,8]. Carbonate can be formed in the anode catalyst layer resulting in low anode pH and reduction of diffusion efficiency. The current density has a significant effect on the cell degradation from CO₂ via carbonation process whereas the cell operating temperature has a minor impact on this issue [9]. The anion exchange membrane fuel cell performance losses by functional group carbonation can be reduced when this fuel cell was operated at current density higher than 1 A/cm². In addition, the flexible fuel usage and low fuel crossover are also the main advantage of this fuel cell [10]. Although alkaline anion exchange membrane fuel cells are still in the early stages of development, their performance almost equal to proton exchange membrane fuel cells with the similar membrane thickness when non-platinum catalysts at the cathode of alkaline anion exchange fuel cell membranes are applied [11].

In the first stage of anion exchange membrane fuel cell development, the relatively low conductivities of anion exchange membranes is the main challenge. Compared to proton exchange membrane, the diffusion coefficient of hydroxide ions in anion exchange membranes is around four times lower than that of proton. However, the anion exchange membrane fuel cell performance has been improved in the last decade because of the progress from the development of membranes with higher anion conductivity [10]. In addition, water transport is the important issue to keep the high performance of anion exchange alkaline fuel cells. In contrast with proton exchange membrane fuel cells, the water (vapor phase) and oxygen are reactants in the cathode and water is produced at the anode for anion exchange alkaline fuel cells. Furthermore, water transports from the cathode to anode due to hydroxide conductivity via electro osmotic drag mechanism. The systematic difference leads to the new challenge of water management. The performance of alkaline anion exchange membrane fuel cells can be improved by sustaining hydration of the cathode, resulting in sufficient water content in the membrane and high hydroxide conductivity. However, too much water at the anode may cause pore flooding in the electrodes, thus leading to a higher mass transfer resistance. The important parameters for developing the water transport model. In addition, the ion conductivity and water uptake of anion exchange multi-block copolymer membranes with a fluorine moiety was studied by Kim et al. [14]. They tried to enhance the hydroxide conductivity by using anion exchange membranes with new fluorinated monomers. The results showed that high anion conductivity of the developed membrane and the fuel cell can be achieved at the current density of 310 mA/cm² at 0.6 V and 70 °C.

Generally, the water transport inside anion exchange membrane fuel cells consists of both electro-osmotic drag and water permeation whereas the in-situ measurement of the water permeation through membranes is complicated [15]. Luo et al. [16] studied ex-situ measurements of the water permeation through anion exchange membranes. The hexamethyl-p-terphenyl poly (dimethylbenzimidazolium) (HMT-PMBI) was compared with a commercial anion exchange membrane (AEM), Fumapem® FAA-3, Nafion membranes. HMT-PMBI possessed showed larger effective internal water permeation coefficient. The liquid water permeation is one order of smaller magnitude compared to that of vapor water permeation. In addition, Omasta et al. [17] investigated the effect of feed gas flow rates, the use of hydrophobic and hydrophilic gas diffusion layers, temperatures, and relative humidity on the performance of alkaline anion exchange membrane fuel cells with the consideration of balancing between membrane hydration and electrode flooding/dry-out. They reported that the operation at higher temperature can mitigate the flooding problem and keep high levels of membrane hydration. Also, the design of relative humidity has a significant effect on the drying out of the membrane and flooding at catalyst and gas diffusion layer at cathode. Zhang et al. [18] also used the electrolyte monomers to synthesize anion-exchange membranes with different hydrophilicity/hydrophobicity using a pore-filling technique. They found that a highly hydrophilic membrane can enhance water permeation from anode to cathode resulting in the improvement of the ion conductivity and the reduction of flooding problem at the anode. Also, one dimensional and steady state model of anion exchange membrane fuel cells was studied by Sohn et al. [19] with the consideration of water transport inside the cell. They reported that anode humidification is important to maintain optimal cell performance. Machado et al. [20] investigated the effect of flow direction in the anode and cathode channel on the anion exchange membrane fuel cell performance. They concluded that the different flow modes have slightly impact on the cell performance. The small back diffusion of water from the anode to the cathode was obtained and thus the operation at low relative humidity causes the membrane dehydration.

The water management and flooding problem of solid-state alkaline fuel cells with pure hydrogen operation were studied by Oshiba et al. [21]. The flood region was estimated by the calculation of relative humidity at the anode outlet. They found that the using thin anion exchange membranes and increasing the anode flow rate can suppress the flooding problem. They also concluded that the operating conditions and material properties of the fuel cell is the important parameters to manage the water transport and improve the performance of anion exchange alkaline fuel cells.

Although the water management has an important role in maintaining and encouraging alkaline anion exchange membrane fuel cell performance, only few numbers of numerical modeling and experimental works have been investigated the characteristics of water transport in alkaline anion exchange membrane fuel cells [22]. The understanding of the fundamentals of water transport and the development of water management strategies are required to overcome this limitation of this technology [23]. The liquid water removal from the anode is necessary to prevent the flooding problem. The encouragement of water permeation or water back diffusion from the anode to cathode is the effective way not only to mitigate flooding problem but also to increase the oxygen relative humidity and water vapor pressure at the cathode. Due to higher water production at the anode than water consumption at the cathode, the concept of the unbalanced pressure between anode and cathode to facilitate the water back diffusion from the anode side to cathode side was analyzed. For unbalanced pressure
concept, the cathode side is operated at low pressure whereas the anode side is operated at high pressure. Due to the pressure gradient, the prevention of anode flooding and increasing of oxygen relative humidity simultaneously occur. In this work, the alkaline anion exchange membrane fuel cells was theoretically investigated with the consideration of the water transport through the membrane. The effects of key operating parameters such as the cathode relative humidity, anode relative humidity, cathode pressure, anode pressure and membrane thickness on the cell performance were studied when the unbalanced pressure operation was applied to enhance water back diffusion from the anode side to the cathode side.

2. Mathematical model of an alkaline anion exchange membrane fuel cell

The electrochemical model and the mass transport model of the alkaline anion exchange membrane fuel cell are applied to investigate its performance at isothermal and steady state conditions with the consideration of the water transport across the membrane when the Tokuyama membranes with the thickness of 10 µm and 28 µm are used. In addition, pure hydrogen and clean air (no CO₂ contamination) are used as reactants. Schematics of the water transport of the alkaline anion exchange membrane fuel cell is presented in Fig. 1.

For this fuel cell, water is produced at the anode side and hydroxide ion is diffused through the membrane from the cathode to anode with water as electroosmotic drag mechanism. Therefore, water content in anode is almost higher than that in cathode and water can permeate from the anode to the cathode because of the water concentration difference. Also, the pressure gradient is another factor which causes water transport between the anode and the cathode in the case of the unbalanced pressure operation between the anode and the cathode. Considering the numerical procedure, the composition of reactants and product at the interface between gas diffusion layer and catalyst was calculated from the diffusion model of both anode and cathode sides while mole fractions at the inlet and gas diffusion layer (GDL) thickness were specified. Also, the water transport from ion conductivity mechanism, concentration gradient and pressure gradient was taken into account. The calculated compositions from the diffusion model were used to obtain cell voltage. The numerical procedure of performance evaluation of the alkaline anion exchange membrane fuel cell was presented in Fig. 2.

2.1. Mass transport model

In this work, the reactants, hydrogen and air with water are fed to the cell in the flow channel of the anode and the cathode sides and then diffuse through the gas diffusion layer to reach the catalyst layer. At the flow channel, the fraction of hydrogen and oxygen at the inlet are used as hydrogen and oxygen along the flow channel. The mass transport in the gas diffusion layer is considered only in the diffusion flux direction [24]. The Stefan Maxwell equation as shown in Eq. (4) is used to represent the diffusion model of the reactants in the gas diffusion layer. The water produced from electrochemical reactions at the anode is assumed to be in the liquid phase.

$$\frac{dx_i}{dz} = \frac{RT}{P} \sum x_i N_i - x_i N_i \frac{D_{ij}}{D_{eff}}$$  \hspace{1cm} (4)

The diffusion model for the anode side are shown as follows:

$$\frac{dx_{H_2}}{dz} = \frac{RT}{P} \left( x_{H_2} (N_{H_2,a} + N_{H_2,d}) - x_{H_2} N_{H_2} \right) \frac{D_{H_2}}{D_{eff} H_2O}$$  \hspace{1cm} (5)

$$\frac{dx_{O_2}}{dz} = \frac{RT}{P} \left( x_{O_2} N_{O_2} - x_{O_2} (N_{O_2,a} + N_{O_2,d}) \right) \frac{D_{O_2}}{D_{eff} H_2O}$$  \hspace{1cm} (6)

The diffusion model of water, oxygen and nitrogen at the cathode side are presented in Eq. (7)–(9).

Fig. 1. Schematics of the water transport of the alkaline anion exchange membrane fuel cell.

Fig. 2. Numerical procedure of performance evaluation of the alkaline anion exchange membrane fuel cell.
Table 1
Molar flux of each component at the anode and the cathode side of the alkaline anion exchange membrane fuel cell.

<table>
<thead>
<tr>
<th>Components</th>
<th>Molar flux</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen</td>
<td>( N_{H_2} = \frac{1}{ \gamma_{H_2}} )</td>
</tr>
<tr>
<td>Oxygen</td>
<td>( N_{O_2} = \frac{1}{ \gamma_{O_2}} )</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>( N_{N_2} = 0 )</td>
</tr>
<tr>
<td>Water</td>
<td>( N_{H_2O} = \frac{1}{ \gamma_{H_2O}} )</td>
</tr>
</tbody>
</table>

\[
dx_N = \frac{RT}{\gamma_N} \left( x_{N_a} N_{N_2} - x_{N_c} (N_{N_2,c} - N_{N_2,d}) \right) + x_{N_a} N_{N_2} - x_{N_c} (N_{N_2,c} - N_{N_2,d}) \frac{D_{\gamma_{N_2}H_2O}}{D_N^{\gamma_{N_2}H_2O}}
\]

The molar flux of each component at the anode and the cathode side of the alkaline anion exchange membrane fuel cell is shown in Table 1.

Molar flux of each component is from the electrochemical reaction and the water transport across a membrane electrode assembly (N\(_{\gamma}\)). The water vapor flux across a membrane electrode assembly can be explained by the combined effect of the electro-osmosis drag force, the water permeation from the concentration gradient and the water back diffusion from the pressure gradient (Pressure difference between the anode and the cathode). The electroosmotic drag (n\(_{\gamma}\)) and water diffusivity (D\(_{\gamma}\)) equations are adapted from the proposed correlation of Jiao et al. [25] and they can be calculated from the correlation as shown in Eqs. (10) and (11), respectively.

n\(_{\gamma}\) = 0.183\(\lambda\) + 1.3

\[
x_N = \frac{RT}{\gamma_N} \left( x_{N_a} N_{N_2} - x_{N_c} (N_{N_2,c} - N_{N_2,d}) \right) + x_{N_a} N_{N_2} - x_{N_c} (N_{N_2,c} - N_{N_2,d}) \frac{D_{\gamma_{N_2}H_2O}}{D_N^{\gamma_{N_2}H_2O}}
\]

The electroosmotic drag and water diffusivity is related to water content (\(\lambda\)) which is defined as:

\[
\lambda = \begin{cases} 
0.0051 \lambda + 1.3 & \text{for } 0 \leq \lambda \leq 14 \\
- (23.2404 + 4.513 \lambda - 0.28926 \lambda^2 + 0.006131 \lambda^3) & \text{for } 14 \leq \lambda \leq 19 \\
\times (T - 303.15) / 10^{10} - (79.826 + 17.928 \lambda) & \text{for } \lambda > 19 \\
- 13.329 \lambda^2 + 0.03337 \lambda^3 & \text{for } \lambda > 19 \\
-41.916 + 0.006131 \lambda^3) \times (T - 303.15) + 8.5139 & \text{for } \lambda > 19
\end{cases}
\]

\[
D_{\gamma} = \begin{cases} 
(4.908 - 0.01537 \lambda - 0.205 \lambda) \times 10^{-10} & \text{for } 0 < \lambda < 1 \\
(4.908 - 0.01537 \lambda - 0.205 \lambda) \times 10^{-10} & \text{for } 1 < \lambda < 3
\end{cases}
\]

2.2. Electrochemical model

To design and determine the performance of anion exchange membrane fuel cells, the electrochemical model is a key to understand the relation between voltage and current density. The cell voltage can be calculated by subtracting the open circuit voltage (Eq. (13)), the maximum voltage, by the anode and cathode activation losses as well as the ohmic loss as shown in Eq. (14). The parameters used for the simulation in this work are presented in Table 2.

Table 2
Parameters for the electrochemical model of the alkaline anion exchange membrane fuel cell [12,26].

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistivity of flow channel plate ((\rho_{\text{chan,chan}}))</td>
<td>(6 \times 10^{-5})</td>
<td>(\Omega) m</td>
</tr>
<tr>
<td>Resistivity of electrode ((\rho_{\text{elec,elec}}))</td>
<td>(6 \times 10^{-5})</td>
<td>(\Omega) m</td>
</tr>
<tr>
<td>Gas diffusion layer thickness ((d_{\text{DL}}))</td>
<td>(20 \times 10^{-6})</td>
<td>m</td>
</tr>
<tr>
<td>Catalyst layer thickness ((d_{\text{cat}}))</td>
<td>(10 \times 10^{-6})</td>
<td>m</td>
</tr>
<tr>
<td>Reference concentration of oxygen ((C_{\text{ref,O}_2}))</td>
<td>10</td>
<td>mol m(^{-3})</td>
</tr>
<tr>
<td>Reference concentration of hydrogen ((C_{\text{ref,H}_2}))</td>
<td>20</td>
<td>mol m(^{-3})</td>
</tr>
<tr>
<td>Reference concentration of water ((C_{\text{ref,H}_2O}))</td>
<td>2000</td>
<td>mol m(^{-3})</td>
</tr>
<tr>
<td>Transfer coefficient ((\alpha))</td>
<td>0.5</td>
<td>-</td>
</tr>
<tr>
<td>Anode reference exchange current density ((i_{\text{ref,a}}))</td>
<td>(1 \times 10^{0})</td>
<td>A m(^{-2})</td>
</tr>
<tr>
<td>Cathode reference exchange current density ((i_{\text{ref,c}}))</td>
<td>(1 \times 10^{4})</td>
<td>A m(^{-2})</td>
</tr>
<tr>
<td>Electrical conductivity of membrane ((\kappa_{\text{mem}}))</td>
<td>0.38</td>
<td>S m(^{-1})</td>
</tr>
<tr>
<td>Electrical conductivity of electrode ((\kappa_{\text{elec}}))</td>
<td>750</td>
<td>S m(^{-1})</td>
</tr>
</tbody>
</table>

The activation loss at the cathode and the anode are calculated from the Butler-Volmer Equation adapted from Jiao et al. [12] as presented in Eqs. (15)–(18).

\[
i_a = i_{\text{ref,a}} \left( \frac{\epsilon_{\text{ref,H}_2} \gamma_{\text{H}_2}^{0.5}}{\epsilon_{\text{ref,O}_2} \gamma_{\text{O}_2}} \right) \left( \exp \left( \frac{2AF}{RT} \eta_{\text{act,a}} \right) - \exp \left( -\frac{2AF}{RT} \eta_{\text{act,a}} \right) \right)
\]

\[
i_c = i_{\text{ref,c}} \left( \frac{\epsilon_{\text{ref,O}_2} \gamma_{\text{O}_2}^{0.5}}{\epsilon_{\text{ref,H}_2} \gamma_{\text{H}_2}} \right) \left( \exp \left( -\frac{4AF}{RT} \eta_{\text{act,c}} \right) + \exp \left( -\frac{4AF}{RT} \eta_{\text{act,c}} \right) \right)
\]

\[
i_a = i_{\text{ref,a}} \exp \left( -\frac{10}{353.15} \right)
\]

\[
i_c = i_{\text{ref,c}} \exp \left( -\frac{7900}{353.15} \right)
\]

Furthermore, the ohmic loss can be determined from the resistance of electron and ion transport in the bipolar plate, the porous media and the membrane as follows [27]:

\[
\eta_{\text{ohm}} = (R_{\text{elec,cell}} + R_{\text{cat,cell}} + R_{\text{ohm,cell}} + R_{\text{ohm,mem}}) \times i
\]

The resistance of electron and ion transport can be calculated from the conductivity of electron and hydroxide ion and Eq. (20).

\[
a_{\text{elec}} = 0.1334 + 3.382 \times 10^{-4} T + (0.01148 T - 3.909) a_{\text{tet}} - (0.0669 T - 23.01) a_{\text{tet}}^{-2}
\]

\[
a_{\text{ion}} = 0.0051 + 0.144 \times 10^{-10} \lambda + 23.2404 + 4.513 \lambda - 0.28926 \lambda^2 + 0.006131 \lambda^3
\]

3. Results and discussion

The mathematical model of alkaline anion exchange membrane fuel cells was performed in Matlab program with the consideration of the water transport through the membrane. The effects of operating conditions on the cell performance were analyzed. The base case operating conditions of alkaline anion exchange membrane fuel cells are presented in Table 3.

3.1. Validation

To confirm the reliability of the model and the simulation results, the simulation results was compared with experimental data reported by Huo et al. [27] and presented in Fig. 3. For the comparison, pure hydrogen and air are used as reactants with the cell temperature of 323.15 K and pressure of 1 atm, Tokuyama A201 thickness of 28 \(\mu\)m.
and the anode and cathode relative humidity are 100%. It was found that the simulation results of the hydrogen alkaline anion exchange membrane fuel cell are in agreement with the experimental data.

### 3.2. Effect of relative humidity

The polarization curve from the simulation results at various cathode relative humidity and anode relative humidity conditions are presented in Fig. 4. The relative humidity has a direct effect on the water content in the membrane which affects efficiency of the ion conductivity and thus the cell performance. Considering the effect cathode relative humidity on the polarization curve as shown in Fig. 4(a), it is observed that an increase in the cathode relative humidity enhances the alkaline anion exchange membrane fuel cell performance. As the increased gas humidity causes more vapor water in the fuel, the hydrosxide conductivity increases and the ohmic loss reduces. Dry fuel gas leads to the dehydration of the membrane and thus the cell performance decreases rapidly. It is noted that water is needed for the hydrosxide conductivity of the anion exchange membrane due to the electro osmotic mechanism. As seen in Fig. 4(a), the cell performance drop is observed at low cathode relative humidity and high current density. This is because high amount of water transfers from the anode to the cathode from electro osmotic mechanism at high current density and thus water is not sufficient to run the electrochemical reaction and maintain suitable water content in the membrane. Therefore, the sufficient amount of water is principally guaranteed with the operation at high cathode relative humidity. An increase in humidify of inlet air leads to the increasing of the membrane conductivity and the improvement of cell performance. From simulation results, it can be concluded that the humidified air enhances the cell performance while the best performance is achieved at fully humidified cathode.

Furthermore, the effect of anode relative humidity on the cell performance is shown in Fig. 4(b). It is observed that the fuel cell performance increases with the increasing the anode relative humidity. From the electrochemical reaction, water is consumed at the cathode and produced at the anode. Although water is not required for the reaction and ion conductivity in the anode side, amount of water in the inlet feed stream at the anode has an effect on the water content in the membrane and amount of water at the cathode because of the water back diffusion from the anode to the cathode from the concentration and pressure gradients as presented in Fig. 5 which shows the net water flux from cathode to anode which accounts for the water transport from three different kinds, i.e., the electro-osmosis drag force, the anode relative humidity and the cathode relative humidity. Therefore, the operation at high anode relative humidity improves the performance of anion exchange membrane fuel cells. In addition, the anode relative humidity has more impact on the cell performance than the cathode relative humidity as seen in Fig. 4.

Considering the influence of the anode relative humidity and the cathode relative humidity on the net water flux from the cathode to the anode of the anion exchange membrane fuel cell as shown in Fig. 5. It is found that the net water flux has negative values that mean water transfer from the anode to the cathode is higher than the water transport from the cathode to anode. In addition, the operation at anode relative humidity of 100% and the cathode relative humidity 50% has the lowest net water flux compared to the other conditions. This is because more water content at the anode facilitate water back

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**Table 3**

The base case operating conditions of alkaline anion exchange membrane fuel cells.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell temperature (K)</td>
<td>333.15</td>
</tr>
<tr>
<td>Pressure (atm)</td>
<td>1</td>
</tr>
<tr>
<td>Anode relative humidity (%)</td>
<td>50</td>
</tr>
<tr>
<td>Cathode relative humidity (%)</td>
<td>100</td>
</tr>
<tr>
<td>Membrane thickness (µm)</td>
<td>10</td>
</tr>
</tbody>
</table>

**Fig. 3.** Comparison of the simulation results in this work with the experimental data [27].

**Fig. 4.** Effect of (a) cathode relative humidity and (b) anode relative humidity on the performance of the alkaline anion exchange membrane fuel cell.
permeation from the anode to the cathode.

3.3. Effect of pressure

The effect of pressure on the fuel cell performance and voltage losses is presented in Fig. 6. The pressures at the cathode and anode are maintained at the same level for this simulation results. It is found that the operation at high pressure can slightly enhance the cell performance with several reasons. The partial pressures of reactants at the cathode and anode also increase with the increasing of pressure and thus the activation losses at the anode and cathode reduce as seen in Fig. 6. However, the pressure has a main impact on the ohmic loss at high current density. The ohmic loss reduces when the alkaline anion exchange membrane fuel cell is operated at high pressure. This is because the water activity tend to increase with the pressure and thus the ion conductivity of membrane also enhances resulting in the reduction of membrane resistance and the ohmic loss as seen in Fig. 6.

The effect of the anode and cathode pressure on the cell performance and net water flux across membrane from cathode to anode is presented in Fig. 7. The anode and cathode were operated at the same pressure between 1 to 2 atm. From the simulation results, it is found that the net water flux from the cathode to anode has negative value at all considered pressure. In addition, the net water flux increases with the increasing of the current density. The is because of high concentration gradient and pressure gradient at low water concentration and low water partial pressure at the cathode from the high water consumption at high current density. However, the almost similar net water flux of each operating pressure are observed. Therefore, very small level of water is transfered with the incresing of the anode and cathode pressures at the same level. Consequently, the results show no significant effect of the anode and cathode pressures on the net water transport when the anode and cathode are operated at the similar pressure. However, the cell performance slightly increses with the increasing of pressure due to the reduction of ohmic loss.

3.4. Effect of membrane thickness

The effect of the membrane thickness on the various losses of the anion exchange membrane fuel cell is shown in Fig. 8 when the fuel cell was operated at atmospheric pressure, anode relative humidity of 50% and cathode relative humidity of 100%. From the simulation results, it is found that membrane thickness has no significant effect on the anode activation loss and the cathode activation loss. However, the ohmic loss considerably increases when the membrane thickness increases from 10µm to 28µm. Therefore, the cell performance with the using of membrane thickness of 10µm is better than that of 28µm. Thin membrane is preferred to reduce ohmic loss and improve cell performance as presented in polarization curve in Fig. 9.

3.5. Unbalanced pressure operation

According to water production at the anode and water consumption at the cathode, the concept of the unbalanced pressure operation to facilitate water transport from the anode to the cathode was investigated. For the unbalanced pressure operation, the anode pressures are operated at higher than 1 atm by regulating anode back pressure whereas the cathode pressure is kept at 1 atm to increase water flux from the anode to cathode. In addition, the relative humidity at the cathode and anode are kept at 100% and 50%, respectively. The water vapor pressure at the interface between gas diffusion layer and catalyst layer calculated from the Stefan Maxwell model are presented in Fig. 10. The operation at the anode pressure of 1.5 atm and cathode pressure of 1 atm (case 2) provides the highest value of the cathode water vapor pressure (dash line) compared to the operation at the same anode and cathode operating pressure (case 1 and case 3). This results from the water back diffusion from the anode to the cathode due to the pressure gradient. In addition, almost the same values of the water vapor pressure at the interface between the cathode gas diffusion layer and the cathode catalyst layer are obtained for the case 1 and 2 except at high current density operation. However, the water vapor pressure at
the cathode decreases with the increasing of the current density because of the water consumption in electrochemical reaction at the cathode and the electro osmotic drag from ion conductivity via the anion exchange membrane. Considering the anode partial pressure (solid line) in Fig. 10, its highest value is obtained at the anode pressure of 1.5 atm and cathode pressure of 1 atm (case 2) whereas the operation at anode and cathode pressures at the same pressure in case 1 and 3 provides the quite similar anode water vapor pressure. It is noted that the water vapor pressures at the cathode and anode of all studied conditions are lower the saturated partial pressure ($\approx$ 0.19 atm) at 60°C resulting in no liquid water formation between the gas diffusion layer and catalyst layer.

The voltage losses of the alkaline anion exchange membrane fuel cell with the unbalanced pressure operation ($P_a = 1.5$ atm and $P_c = 1$ atm) was studied and compared with the similar anode and cathode pressure operation ($P_a = 1.5$ atm and $P_c = 1.5$ atm) as shown in Fig. 11. Due to higher water vapor pressure from the unbalanced pressure operation, higher ion conductivity and lower ohmic loss are observed. However, no significant effect on the anode and cathode activation losses is observed for the unbalanced pressure operation compared to the same pressure operation. Although the anode and cathode of the alkaline anion exchange membrane fuel cell are operated at the high pressure (1.5 atm), its ohmic loss is higher than that of the alkaline anion exchange membrane fuel cell with the unbalanced pressure operation ($P_a = 1.5$ atm and $P_c = 1$ atm).

The relation between cell voltage and current density at various anode and cathode operating pressures is shown in Fig. 12 (solid line). It is found that the cell performance slightly enhances when the pressure increases from 1 atm to 1.5 atm with the same anode and cathode operation (case 1 and case 3). However, the considerable increase of cell performance is observed when the anode and cathode are operated with the unbalanced pressure concept (case 2) at 1.5 atm and 1 atm, respectively. This is because the higher water flux across membrane from the anode to the cathode of the unbalanced pressure operation compared to that of the same pressure operation as shown in Fig. 12 (dash line). It is found that the alkaline anion exchange membrane fuel cell has the negative value of the net water flux at almost all studied operating pressures and current densities. The negative values of water flux refer to higher water transport from the anode to the cathode than the water transfer from the cathode to the anode.

In addition, it is observed that the cell performance enhances with the unbalanced pressure operation at all considered membrane thickness when the anion exchange membrane fuel cell is run at the anode pressure of 1.5 atm and the cathode pressure of 1 atm as shown in

![Fig. 8. Effect of membrane thickness on the anode activation loss, cathode activation loss and ohmic loss of the alkaline anion exchange membrane fuel cell.](image)

![Fig. 9. Polarization curve of the alkaline anion exchange membrane fuel cell at different membrane thicknesses.](image)

![Fig. 10. Water vapor pressure at the interface between the gas diffusion layer and catalyst layer of the the alkaline anion exchange membrane fuel cell at different current densities and pressures.](image)

![Fig. 11. Voltage losses of the alkaline anion exchange membrane fuel cell at different current densities and operating pressures at the anode and cathode.](image)
results shown in Fig. 14. For this figure, the effects of the membrane thickness and pressure on the net water flux across the membrane from the cathode to anode of the anion exchange membrane fuel cell are presented. From the simulation results, the net water flux of membrane thickness of 28 µm are the positive values whereas the negative values of the net water flux are observed for the membrane thickness of 10 µm. This is because the use of thin membrane can facilitate the water back diffusion from the anode to cathode whereas water hardly transports from the anode to cathode for the thick membrane and thus electro osmotic drag is the main water transport mechanism for this membrane. Therefore, the use of thin membrane has the positive effect in terms of the reduction of the ohmic loss and the improvement of the cell performance.

4. Conclusions

The performance of the alkaline anion exchange membrane fuel cell was numerically investigated with the consideration of water transport across the membrane. In addition, the cell operation at different pressures between the anode and cathode to facilitate water back diffusion was analyzed as the unbalanced pressure concept. The influences of the anode relative humidity, cathode relative humidity, anode pressure, cathode pressure and membrane thickness are also studied. The improvement of the cell performance is observed at high cathode relative humidity because of the reduction of the cathode activation and the ohmic loss. At the same time, the anode relative humidity has a significant effect on the cell performance because this parameter has the direct effect on the water back diffusion from the anode to cathode and thus high anode relative humidity operation can maintain suitable level of cathode water reduced from the reaction consumption in the reaction and hydroxide conducting mechanism. In addition, the use of thin membrane and unbalanced pressure operation result in high water flux across the membrane from the anode to the cathode and thus the significant improvement of the cell performance is observed. The main voltage loss of the alkaline anion exchange membrane fuel cell is the cathode activation loss and the ohmic loss which considerably increases at high current density and with the use of thick membrane. The use of unbalanced pressure operation can enhance water vapor pressure at the cathode resulting in the reduction of ohmic loss and the improvement of the cell performance.

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