Effect of different fuel options on performance of high-temperature PEMFC (proton exchange membrane fuel cell) systems

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**Abstract**

High-temperature proton exchange membrane fuel cells (HT-PEMFCs) have received substantial attention due to their high CO (carbon monoxide) tolerance and simplified water management. The hydrogen and CO fractions affect the HT-PEMFC performance and different fuel sources for hydrogen production result in different product gas compositions. Therefore, the aim of this study is to investigate the theoretical performance of HT-PEMFCs fueled by the reformate gas derived from various fuel options (i.e., methane, methanol, ethanol, and glycerol). Effects of fuel types and CO poisoning on the HT-PEMFC performance are analyzed. Furthermore, the necessity of a water-gas shift (WGS) reactor as a CO removal unit for pretreating the reformate gas is investigated for each fuel type. The methane steam reforming shows the highest possibility of CO formation, whereas the methanol steam reforming produces the lowest quantity of CO in the reformate gas. The methane fuel processing gives the maximum fraction of hydrogen ($\approx 0.79$) when the WGS reactor is included. The most suitable fuel is the one with the lowest CO poisoning effect and the maximum fuel cell performance. It is found that the HT-PEMFC system fueled by methanol without the WGS reactor and methane with WGS reactor shows the highest system efficiency ($\approx 50\%$).

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1. **Introduction**

Traditionally, a combustion process of petroleum-derived fuel, which is a limited resource, is used for power generation. However, this process has low efficiency and releases greenhouse gases, which are the major cause of global warming. Because of the need for clean energy and an efficient method for clean energy production, substantial effort has been directed toward the development of fuel cell technology for electricity generation. Fuel cells have been continuously developed to supply considerable energy demand. In addition to electricity, fuel cells generate only water and heat as by-products and are thus environmentally friendly and sustainable [1].

Among the several types of fuel cells, polymer electrolyte membrane or proton exchange membrane fuel cells (PEMFCs) are very attractive for automobile, residential and portable applications because they are operated at low temperatures of approximately 333–353 K, which allows them to start up very quickly. In addition, they exhibit a good response to changes in power demand and high current density [2]. However, there are some difficulties in the operation of PEMFCs that need to be solved for real applications. In general, high-purity hydrogen with few contaminants, especially carbon monoxide (CO), is required for PEMFC. The presence of CO in the hydrogen feed will poison the Pt catalysts at the anode of the PEMFC, reducing the active sites available for electrochemical reactions. Therefore, a complex CO removal process of the hydrogen feedstock is needed to reduce the CO concentration to less than 10 ppm [3]. Another important problem influencing PEMFC operation is water management because of the low operating temperatures and the specific characteristics of the membrane used in the PEMFC [4,5]. The fuel must be saturated with water to avoid the dry-out condition of the polymer membrane. Nevertheless, the excess water may condense into the liquid phase and cause a flooding problem in the cathode gas diffusion layer, which would block oxygen to transport to the catalyst layer, resulting in fuel cell voltage and performance losses.
To solve the problem mentioned above, a high-temperature proton exchange membrane fuel cell (HT-PEMFC) operating at temperatures of approximately 373–473 K has recently been developed. As a result of the high-temperature operation of the PEMFC, the transport of water within the PEMFC is simplified and electrochemical reaction rates at the anode and cathode are increased. The flooding problem is eliminated because water is present in the vapor phase only at temperatures above 373 K. However, such conditions can lead to the dehydration of the membrane and the loss of membrane ionic conductivity. The efficiency of conventional PEMFCs relies on water content in the membrane; thus, its performance is depressed when the water content is low. To overcome this difficulty, a polybenzimidazole (PBI) has been developed for use in HT-PEMFCs that can be operated at low relative humidity. In addition, it is usually doped with phosphoric acid or other dopants to increase the proton conductivity [6,7].

The enhancement of CO tolerance is an important benefit of operating PEMFCs at high temperatures. From a thermodynamic point of view, the adsorption of CO on the Pt surface is reduced by increasing the temperature and/or decreasing the CO concentration [8]. The possibility of hydrogen adsorption, which is less exothermic than CO adsorption, would increase at higher operating temperatures. Moreover, the CO purification process of the HT-PEMFC system is simpler than that of the conventional PEMFC. The preferential oxidation, pressure swing adsorption or membrane separation is unnecessary for the HT-PEMFC system. Thus, the hydrogen-rich gas from the fuel reforming processes can be fed to the HT-PEMFC directly without the need for the sophisticated CO removal process; instead, only a water-gas shift (WGS) reactor, which functions as a simple CO removal unit, is needed.

Recently, the fuel cell integrated with a fuel processor, which allows hydrogen generation from hydrocarbon fuels, and the combined heat and power (CHP)-based PEMFC system is continuously developing to avoid the issue of hydrogen infrastructure and increase the system efficiency [9,10]. In addition, the performance of conventional PEMFC and HT-PEMFC systems for various applications has been studied [9,11,12]. At present, natural gas is the most common fuel for hydrogen production because of its cost effectiveness for industrial applications. However, natural gas is limited and insufficient for the increased energy demand. Methanol has also received much more attention as a hydrogen-production feedstock for PEMFCs because it is a small molecule and is thus easily converted into hydrogen. The high hydrogen-to-carbon ratio and the absence of carbon—carbon bonds in methanol allow it to be reformed into hydrogen at low operating temperatures [13]. These conditions favor the water-gas shift reaction in the reformer, which reduces the CO content in the reformate gas.

Because of the increased power demand and environmental concerns, the development of a new, sustainable feedstock for hydrogen production is necessary. Ethanol and glycerol as renewable resources will become the most important fuel sources [14–17]. Ethanol appears to be an appropriate fuel for the production of hydrogen for PEMFCs because it can be reformed at low temperatures, similar to methanol. Because the use of biodiesel for diesel engines is growing, the by-product glycerol that is generated from the conventional biodiesel production process is also a potential fuel for use in the production of hydrogen [18–21]. Because hydrogen and CO have an effect on the HT-PEMFC performance and different fuel sources used for hydrogen production result in different product gas compositions, the most suitable fuel for the HT-PEMFC system should be investigated.

The aim of this work is to theoretically study the performance of HT-PEMFCs fueled by various fuel options. The model of HT-PEMFC, which considers the effect of CO poisoning, is used to analyze HT-PEMFC performance. Methane and other oxygenated hydrocarbons, such as methanol, ethanol and glycerol, are used to produce hydrogen-rich gas (reformate gas) for the HT-PEMFC. In addition, the necessity of a water-gas shift reactor to function as a CO removal unit for pretreating the reformate gas before it is fed to the HT-PEMFC is investigated for each fuel type. The most suitable fuel and optimal conditions, which are those resulting in the lowest CO poisoning effect and the maximum fuel cell performance, are examined.

2. Description of the HT-PEMFC system

The HT-PEMFC system considered here consists of two main parts, which are fuel-processing process and HT-PEMFC. The mathematical models of the HT-PEMFC system are developed and coded in Matlab.

2.1. Fuel-processing process

Considering the fuel-processing process for HT-PEMFC, the steam reforming process with and without water-gas shift reactor is considered in this work. A thermodynamic approach is used to analyze the reforming process with different fuels, i.e., glycerol, ethanol, methanol and methane. For a given set of substances involved in the reforming reactions, the equilibrium composition of the reformate gas from steam reformers is directly determined by solving the minimization problem of the Gibbs free energy (Eq. (1)) [22].

\[
\min_{n_i \in \text{reactants}} \left( G_f(T, P) \right) = \sum_{i=1}^{C} n_i G_i = \sum_{i=1}^{C} n_i \left( C_i^f + RT \ln \frac{T}{T_0} \right) \tag{1}
\]

where \( C \) is the total number of components in the reaction system and \( n_i \) is the number of moles of each gaseous component. Regarding the conservation of atomic species, \( n_i \) must satisfy the element balance in Eq. (2).

\[
\sum_{k=1}^{w} n_i a_{ik} - A_k = 0 \quad (k = 1, 2, \ldots, w) \tag{2}
\]

where \( a_{ik} \) is the number of atoms of element \( k \) in component \( i \), \( A_k \) is the total number of atoms of element \( k \) in the reaction mixture, and \( w \) is the total number of elements.

The optimization problem mentioned above is finding the set of \( n_i \) that minimizes \( G \) for the specified \( T \) and \( P \) and that satisfies the element balances. To solve such an optimization problem, Lagrange multipliers method is applied [22]. Table 1 shows the set of substances involved in the reforming process of each type of fuel. Based on experimental data of the low-temperature methanol steam reforming, methane is not included in the set of substances in the methanol reforming process [23]. However, methane is a key component of the steam reforming of several fuels, such as natural gas, glycerol, and ethanol [24–26]. For WGS reactor, it is modeled as an equilibrium reactor and only the water gas shift reaction is occurred in this reactor [27].

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Set of substances</th>
</tr>
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<tbody>
<tr>
<td>Glycerol (C₃H₈O₃)</td>
<td>C₂H₅OH, CH₂, CO₂, CO, H₂O, H₂</td>
</tr>
<tr>
<td>Ethanol (C₂H₅OH)</td>
<td>C₂H₅OH, CH₄, CO₂, CO, H₂O, H₂</td>
</tr>
<tr>
<td>Methanol (CH₃OH)</td>
<td>CH₃OH, CO₂, CO, H₂O, H₂</td>
</tr>
<tr>
<td>Methane (CH₄)</td>
<td>CH₄, CO₂, CO, H₂O, H₂</td>
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</tbody>
</table>
2.2. HT-PEMFC

The HT-PEMFC is a promising PEMFC technology that has been developed to address the CO poisoning problem. Because the hydrogen and CO fractions of the reformate gas depend on the raw materials used for hydrogen production, HT-PEMFC systems running on different fuels produce different power outputs. In this study, various fuel options for producing the reformate gas from the steam reforming process for HT-PEMFC operation are considered with the aim of finding a suitable fuel and an appropriate fuel processing method for each fuel for this HT-PEMFC system.

An electrochemical model is used to evaluate the cell performance. The relation of voltage and current density for HT-PEMFC is shown in Eq. (3). The cell voltage ($E_{cell}$) is calculated from the reversible cell potential ($E_r$) and various voltage losses, which are activation loss at the anode ($\eta_{act,a}$), the activation loss at the cathode ($\eta_{act,c}$) and the ohmic loss ($\eta_{ohmic}$).

$$E_{cell} = E_r - \eta_{act,a} - \eta_{act,c} - \eta_{ohmic}$$

Table 2

<table>
<thead>
<tr>
<th>Electrochemical model of the HT-PEMFC [28,29]</th>
</tr>
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<tr>
<td>Reversible cell potential</td>
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<tr>
<td>Anode activation loss</td>
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<td>Cathode activation loss</td>
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<tr>
<td>Ohmic loss</td>
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</tbody>
</table>

In this work, the catalyst layer is assumed to be an average of the solid electrode and the electrolyte. Fick’s law is applied to explain a transport of gaseous reactants from the gas diffusion layer through an electrolyte film covering the catalyst agglomerates to reach the catalyst active surface and determine the H2 and O2 concentrations at the catalyst active surface covered by the thin polymer/acid film (Eqs. (5) and (6)).

$$\frac{dX_i}{dx} = \frac{RT}{P} \sum \frac{X_i N_i - X_i N_j}{D_j}$$

The concentrations of hydrogen and O2 dissolving at the anode. The concentration of hydrogen and O2 dissolving at the anode and cathode exhaust gases as well as from the high-temperature product gas of the reforming process.

$$P_{FC} = iE_{cell}$$

The system efficiency of the PEMFC integrated with the reforming process is estimated by Eq. (10). The energy required for the reforming process is partially supplied by the heat recovery ($Q_{rec}$) from the anode and cathode exhaust gases as well as from the high-temperature product gas of the reforming process.

$$\eta_{sys} = \frac{P_{FC}}{m_{fuel} \cdot LHV_{fuel} + Q_{ef} - Q_{rec}}$$

Fig. 1. Model solution of the integrated reforming process and HT-PEMFC system.
3. Simulation approach

In this work, the mathematical models describing the fuel processor and the HT-PEMFC are programmed using Matlab. The model solution approach to the reforming process and HT-PEMFC integrated system is shown in Fig. 1. The reformer temperature, reformer pressure and steam-to-carbon (S/C) ratio are pre-specified. The molar flow rate and composition of the reformate gas are calculated from the direct minimization of Gibbs free energy using the Lagrange multipliers method. The fsolve function in Matlab is employed to solve a set of non-linear thermodynamic equations. Subsequently, the product gases are fed to the flow channel of the HT-PEMFC. All the model parameters in the HT-PEMFC model can be found in our previous work[29]. The outlet gas compositions are calculated from the fuel utilization and current density. The Stefan–Maxwell equation is used to find the mole fraction of the reactant gases at the gas diffusion layer/film electrolyte interface. In general, gaseous reactants diffuse through the electrolyte film layer before reaching the catalyst active area, and Fick’s law is applied to explain this phenomenon. Then, the electrochemical model is applied to calculate the activation loss, ohmic loss and cell voltage, and the $V-I$ curve of the HT-PEMFC is plotted. Finally, the system efficiency is calculated by considering the heat recovery. Heat from hot reformate gases and the anode and cathode off gases are recovered and used to preheat and vaporize the reformer feeds (i.e., fuel and water). The amount of the recovered heat is calculated from enthalpy changes.

4. Results and discussion

A comparison of the different fuels, i.e., glycerol, methanol, ethanol and methane, used for the steam reforming process to produce hydrogen-rich gas for the HT-PEMFC is investigated in this work. The integrated steam reforming and HT-PEMFC systems with and without a water-gas shift reactor are considered. The suitable operating conditions of the steam reformer are first determined by considering the quantity of CO in the obtained reformate gas. Subsequently, the performance of the HT-PEMFCs using different fuel feedstock is analyzed.

The presence of CO (dry basis) in the reformate gas derived from the reforming of glycerol, ethanol, methane and methanol is shown in Figs. 2–5, respectively. A similar %CO trend is observed for all of the fuel types; the %CO increases as the temperature increases but decreases as the steam-to-carbon feed ratio (S/C) increases. This implies that high S/C and low temperature are the favorable operating conditions for producing reformate gas for HT-PEMFCs. Considering the steam reforming of glycerol and ethanol (Figs. 2 and 3), %CO is lower than 10%, the highest CO tolerance value of the HT-PEMFC [30,31], when the reformer is operated at low temperatures.
temperatures (800–900 K) for all of the studied S/C ratio conditions. However, at the reformer temperature of 1000 K, %CO is higher than 10% when the reformer is operated at an S/C ratio of less than 5. Therefore, to keep the %CO in the reformate gas lower than 10%, the glycerol and ethanol reformers should not be operated at a temperature of 1000 K and an S/C of less than 5. For the methane steam reforming (Fig. 4), a considerable CO content is generated by this process. The operation of the methane reformer at a temperature of 1000 K is unacceptable for HT-PEMFCs at all S/C ratios. However, the steam reforming of methanol, which favors mild conditions, produces an acceptable CO fraction in the reformate gas; the presence of CO in the reformate gas is less than 5% at all of the studied operational ranges (see Fig. 5).

From the simulation results, it can be concluded that to keep the CO concentration at an acceptable level, the glycerol and ethanol reformers can be operated at high temperatures (1000 K) and that the operating S/C ratio should be higher than 5. However, the methane reformer should be operated at a temperature lower than 1000 K for all of the studied S/C ratios to avoid the presence of CO in the reformate gas over the limit. Otherwise, a CO purification unit must be included in the fuel processor. That being so, methanol is an attractive fuel for HT-PEMFCs because the reformate gas produced from the steam reforming of methanol at all studied operating conditions can be used directly in HT-PEMFC. Moreover, the optimal conditions that result in a high hydrogen yield (high S/C and temperature) can be applied to control the reformer with no concern about the amount of CO in the reformate gas. In contrast, the reformer operations of glycerol, ethanol and methane are limited by the CO problem. In this work, the reforming conditions that result in %CO values lower than 10% are used to further investigate the performance and efficiency of the integrated HT-PEMFC system. Under such a constraint, although the selection of the reforming operating conditions for glycerol, ethanol and methane used to produce hydrogen-rich gas for HT-PEMFCs is not based on the conditions that produce high hydrogen yield, these conditions constitute the operational boundary of the steam reformer for the HT-PEMFC. In general, the performance of the steam reformer that give the lowest CO fraction may not present the highest efficiency.

When a water-gas shift reactor is included in the fuel processor to treat the reformate gas from the steam reformer before it is fed into the HT-PEMFC (Figs. 6–9), the CO fraction in the reformate gas of the glycerol and methanol steam reforming is reduced under 2.5% in all of the studied operational ranges. However, the ethanol and methane reformers integrated with the water-gas shift reactor produce reformate gas with high CO content when operating at a temperature of 1000 K and an S/C of one, and thus, these conditions are not selected for further study of the performance of the HT-PEMFC system. In addition, based on the steam reforming processes with and without the water-gas shift, it can be concluded that methanol steam reforming has the highest possibility of CO formation, whereas the methanol steam reforming produces the lowest quantity of CO in the reformate gas. However, the presence of CO is not the only factor affecting the HT-PEMFC performance and system efficiency. The content of hydrogen, its purity, and the energy consumption of the system are also key factors.

Fig. 10 shows the electrical characteristics of the HT-PEMFC running on the reformate gas from the steam reformer when different fuels are used. A similar trend of HT-PEMFC performance is observed when glycerol, ethanol and methane are used as fuels. At high current densities, the fuel cell performance decreases when the reformer temperature increases and the S/C ratio decreases. As mentioned above, the CO formation in the reformer favors high temperatures and low S/C values. In addition, the CO content has no effect on the fuel cell performance when operated at low current density. In the case of methanol reforming, a change in the reformer operating conditions also does not affect the fuel cell performance.
at low current density, but has slight effect on the fuel cell at high current density.

To determine the optimal operating conditions of the steam reformer, the efficiency of the HT-PEMFC system fed by different fuels at various operational conditions is considered. Fig. 11 indicates that the HT-PEMFCs integrated with the steam reforming processes of glycerol, ethanol and methane shows similar trends. At low current density, the efficiency of the HT-PEMFC system is enhanced when the steam reformer is operated at high temperatures and low S/C ratios. In addition to the hydrogen and CO fractions, the system efficiency also depends on the energy consumption. Because CO has a small effect on cell performance at low current density, the operation of the reformer at a high S/C ratio, at which a high level of energy consumption is required to diminish the formation of CO, would be unnecessary. However, the system efficiency is reduced at high current density when the steam reformers are operated at high temperatures and low S/C ratios. This is because CO significantly affects the HT-PEMFC performance when operated at high current density. For the HT-PEMFC integrated with methanol steam reforming, a change in the reforming temperature has no effect on the system efficiency because of low CO content in the reformate gas obtained from the methanol steam reformer. In addition, increasing the S/C ratio to prevent the occurrence of CO is unnecessary. The reformer operated at an S/C ratio of one provides the highest system efficiency. It can be seen that the amount of CO containing in the reformate gas from the methanol reformer has an insignificant effect on HT-PEMFC performance and this result is in agreement with the previous study on HT-PEMFC run on synthesis gas from the reforming of methanol [32].

When considering the efficiency and performance of the HT-PEMFC system with the WGS reactor, the simulation results show that changing the reformer temperature and S/C ratio exerts an insignificant impact on the HT-PEMFC performance, even when different types of fuel are employed. This is because the fraction of CO at the outlet of the WGR reactor is lower than 3%, and thus, the CO poisoning effect on the HT-PEMFC system is small. In addition, the hydrogen content in the reformate gas at the outlet of the WGR reactor is almost the same. However, the efficiency of the HT-PEMFC system with a WGS reactor fed by different fuels varies with the operational conditions of the steam reformer, as shown in Fig. 12. The energy consumption values under different reforming conditions are the main reason underlying the variation of the system efficiency.

The optimal operating conditions of the steam reformer with the highest system efficiency when the HT-PEMFC is operated at voltage of 0.65 V are shown in Table 3. It is seen that the methanol steam reformer can be operated at lower temperatures and S/C ratio. The hydrogen fraction obtained under such optimal conditions is shown in Fig. 13. The methanol and methane reformers achieve the highest hydrogen concentrations when the WGS reactor is not considered in the system, whereas the glycerol

![Fig. 9. %CO in the reformate gas from methanol steam reforming with a water-gas shift reactor at different operating conditions.](image)

![Fig. 10. Polarization curve of the HT-PEMFC fed by the reformate gas from the steam reformer (without the WGS reactor) operated at different S/C ratios and temperatures (for glycerol, ethanol and methane, the black, red and blue lines represent temperatures of 800 K, 900 K and 1000 K, and for methanol, the black and red lines represent temperatures of 448.15 K and 473.15 K, respectively). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)](image)
The reformer produces the lowest hydrogen fraction. In addition, the hydrogen fraction is increased when the WGS reactor is included in the fuel-processing process and glycerol, ethanol and methane are used as reactants. However, the hydrogen obtained from the methanol reformers with and without WGS reactors is the same. In conclusion, the methane reformer with the WGS reactor provides a higher hydrogen fraction than the other case studies.

The efficiency of the HT-PEMFC system with and without a WGS reactor is shown in Fig. 14. For the HT-PEMFC system without the WGS reactor, the HT-PEMFC system integrated with methanol steam reforming shows the highest efficiency, followed by methane, ethanol and glycerol reforming. Although the steam reforming of methane produces reformate gas with a high CO fraction, the energy consumption of this process is lower (no heat of recombination).
vaporization is consumed by this process), and the hydrogen fraction is higher than is observed in the reforming of other fuels. In the case of methanol steam reforming, the HT-PEMFC system without the WGS reactor shows higher efficiency than the system with the WGS reactor, and therefore, the WGS reactor is unnecessary for the methanol steam reforming integrated with the HT-PEMFC system. However, the performance of the HT-PEMFC system is enhanced when the WGS reactor is included in the steam reforming processes of glycerol, ethanol and methane. In addition, the HT-PEMFC system, including the steam reformer and the WGS reactor, provides the highest efficiency when methane is used as a fuel. Regarding all of the studied cases, the integrated methanol steam reforming and HT-PEMFC system without the WGS reactor and the integrated methane steam reforming and HT-PEMFC system with the WGS reactor exhibit the highest system efficiency values.

5. Conclusions

In this study, the HT-PEMFC system integrated with the steam reforming of different fuels, i.e., glycerol, ethanol, methane and methanol, is investigated to analyze the effect of CO and hydrogen fraction in different reformed fuels on cell performance and find the suitable fuel for this system. The steam reforming of methanol results in the lowest CO fraction. The reformate gas obtained from the methanol reformer over the range of studied operating conditions can be fed directly to the HT-PEMFC without the need for a CO purification process; the quantity of CO is below the operational limit of the HT-PEMFC. When considering the reforming of glycerol, ethanol and methane, high S/C ratios and low temperature operation are needed to produce reformate gas with CO contents below the specified limit. A similar trend is also observed for the HT-PEMFC system with a water-gas shift (WGS) reactor. Methanol is the most favorable fuel for the HT-PEMFC system as it results in low CO formation. The reformer operations of glycerol, ethanol and methane strongly affect the HT-PEMFC performance, especially at high current density. The inclusion of the WGS reactor in the reforming processes of glycerol, ethanol and methane can improve the efficiency of the HT-PEMFC system, whereas the WGS reactor is unnecessary for methanol steam reforming integrated with HT-PEMFC. The integrated methanol steam reforming and HT-PEMFC system without the WGS reactor and the integrated methane steam reforming and HT-PEMFC system with the WGS reactor achieve the highest system efficiency values.

Acknowledgments

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Nomenclature

- $C_{\text{dissolve}}$: equilibrium concentration, mole cm$^{-3}$
- $C_r$: concentration on the catalyst surface, mole cm$^{-3}$
- $C_{\text{ref}}$: reference concentration on the catalyst surface, mole cm$^{-3}$
- $D_{\text{eff}}$: binary diffusion coefficient, m$^2$ s$^{-1}$
- $E_{\text{cell}}$: cell voltage, V
- $E_r$: reversible cell potential, V
- $F$: Faraday constant, 96,485 C mol$^{-1}$
- $G$: Gibb free energy, J mol$^{-1}$
- $H$: enthalpy, J mol$^{-1}$
- $K_n$: proton conductivity of LT-PEMFC, S cm$^{-1}$
- $L_C$: catalyst loading, mg cm$^{-2}$
- $LHV$: lower heating value, kJ mol$^{-1}$
- $N$: molar flux, mol s$^{-1}$ m$^{-2}$
- $P$: pressure, atm
- $P_{\text{FC}}$: power output of fuel cell, W
- $Q_{\text{ref}}$: heat required for the steam reforming process, J s$^{-1}$
- $Q_{\text{rec}}$: heat recovery for the steam reforming process, J s$^{-1}$
- $R$: gas constant (=8.314), J mol$^{-1}$ K$^{-1}$
- $RH$: relative humidity
- $S_{\text{Pt}}$: real platinum surface area
- $T$: cell temperature, K
- $X$: mole fraction
- $i$: current density, A m$^{-2}$
- $i_0$: exchange current density, A m$^{-2}$
- $l_m$: membrane thickness, m
- $m$: molar flow rate, mol s$^{-1}$

Table 3

<table>
<thead>
<tr>
<th>Fuels</th>
<th>HT-PEMFC system without WGS reactor</th>
<th>HT-PEMFC system with WGS reactor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$T$ (K)</td>
<td>S/C</td>
</tr>
<tr>
<td>Glycerol</td>
<td>900</td>
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<tr>
<td>Ethanol</td>
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<td>Methanol</td>
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Fig. 13. Mole fraction of hydrogen at the optimal conditions of the reformer with and without the WGS reactor.

Fig. 14. Comparison of the HT-PEMFC systems with and without the WGS reactor.
Greek letters

- $\alpha$: transfer coefficient
- $\gamma$: reaction order
- $\lambda$: water content
- $\theta_{CO}$: CO coverage
- $\theta_{H2}$: H$_2$ coverage
- $\sigma_m$: proton conductivity, S cm$^{-1}$
- $\eta_{ohmic}$: ohmic loss, V
- $\eta_{act}$: activation loss, V
- $\eta_{sys}$: system efficiency

Subscripts and superscripts

- $a$: anode
- $c$: cathode
- $ij$: components “i” and “j”
- $m$: membrane
- $in$: inlet stream
- $out$: outlet stream

References