المجال الحراري لخلية وقود أوكسيدية صلبة مغذية بالميثان: تأثير الكسور المولارية للوقود

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المخالص:

تم خلال العمل الحالي تغذية خلية وقود أوكسيدية صلبة (AS_SOFC) محملة على الأندود ب الخليط من الهواء والوقود عند قناتي الكاثود والأنود على التوالي. كان الوقود عبارة عن خليط من خمس مكونات هي: الميثان (CH₄)، الهيدروجين (H₂)، ثاني أكسيد الكربون (CO₂)، أول أكسيد الكربون (CO)، والبخار (H₂O). حيث جرت عملية تهذيب مباشرة أو خارجية. فعند جانب الأندود جرت عملية تهذيب مباشرة أو غير مباشرة. 

أ. ل. هافسية et al.
Thermal field in SOFC fed by CH₄: Molar fractions effect

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Abstract In the present work, the anode supported solid oxide fuel cell (AS_SOFC) is fed by air and fuel at cathode and at anode channels respectively. The fuel is a mixture of five components: methane (CH₄), hydrogen (H₂), carbon dioxide (CO₂), carbon monoxide (CO) and steam (H₂O), where a reforming phenomenon; an external or an internal one appears. At the SOFC anode side, an indirect or direct reforming phenomenon happens.

The principal aim of this study is the visualization of the temperature fields under heat sources’ effect caused by the direct internal reforming reactions; the steam reforming reaction, the water gas shift reaction and the overall reforming reaction. The temperature gradient is discussed for several inlet fuel molar fractions.

A program in FORTRAN language using the finite difference method is developed. The thermal fields', in the plane perpendicular to the gas flow, is visualized by “Tec plot” program. This study requires a coupling conservation equations (mass, energy and species). The flows are governed by Darcy’s law. The results show that the fuel molar fractions cannot be ignored in the presence of direct internal reforming phenomenon.

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1. Introduction

Demographic growth has encouraged companies to diversify and increase their energy resources. However, this development cannot be accomplished simply by increasing fossil fuel (oil, gas or coal) consumption. Indeed, the energy demand increase associated with resource scarcity currently conducts to oil price increases. This economic problem is accompanied by a major environmental challenge: the use of hydrocarbons generates CO₂ immense emissions that contribute to planet global warming. Therefore, it becomes essential to find alternative concurrently technological solutions to: (i) limit energy consumption, (ii) increase the efficiency of fossil fuel converters into usable energy (electricity and transport) and (iii) develop cleaner sources and energy carriers.

To attain these objectives, it is particularly necessary to develop new energy technologies. Solid oxide fuel cell (SOFC) comes in this context. This technology is indeed the most effective way to convert the hydrocarbon chemical energy into electricity. This transformation takes place at high temperature...
Thermal field in SOFC fed by CH₄:  Molar fractions effect

(600–1000 °C) on the basis of an electrochemical fuel oxidation and oxygen reduction from the air (Laurencin, 2008). This high temperature has a double advantage. First, it assures the provision of easily exploitable high heat in cogeneration. Secondly, it allows the hydrocarbons direct use, primarily natural gas, which can be easily reformed in order to produce hydrogen for SOFC fuel cell. According to the literature review, when it is fed by a fuel other than hydrogen; CH₄, H₂, CO₂, CO, H₂O, molar fractions do not have the same percentage (Table 1).

The present work’s contribution is to study the temperature fields under the heat source effect caused by the direct reforming reactions; the steam reforming reaction, the water gas shift reaction and the overall reforming reaction. The parameter studied is the inlet fuel molar fractions.

2. Physical model

The physical model adopted for the SOFC direct reforming phenomenon simulation is shown in Fig. 1. The first compartment, corresponding to an anode supported planar SOFC fuel cell is fed by fuel and air (Fig. 1(a)). The second one; (Fig. 1(b)) shows the study area. The latter is composed by:

- Two interconnections; anode and cathode interconnections,
- Two electrodes (anode and cathode),
- An electrolyte.

Fig. 1(c) represents the anode, reforming and electrochemical reaction locations, and the anode interconnection. The reactions occurred in the anode and considered in the mathematic model are:

Reforming reactions:
- Steam reforming reaction: \( \text{CH}_4 + \text{H}_2\text{O} \rightarrow 3\text{H}_2 + \text{CO} \) (1)
- Water – gas shift reaction: \( \text{CO} + \text{H}_2\text{O} \rightarrow \text{H}_2 + \text{CO}_2 \) (2)
- Overall reforming reaction: \( \text{CH}_4 + 2\text{H}_2\text{O} \rightarrow 4\text{H}_2 + \text{CO}_2 \) (3)

3. Mathematical model

For this numerical study, the planar SOFC is fueled by gases; air and fuel. The fuel is a mixture of methane (CH₄), hydrogen (H₂), carbon monoxide (CO), carbon dioxide (CO₂) and steam (H₂O). Thermal field’s visualization is made in the plane perpendicular to the gas flow direction of a single cell (Fig. 1). This study requires coupling conservation equations; mass, energy and species. For the momentum equation in the porous electrodes, the flow is modeled using Darcy’s law.

\[
U = -\frac{k}{\varepsilon \mu} \text{grad}(p)
\]

where \( U \) (m s\(^{-1}\)) is the velocity, \( k \) (m\(^2\)) is the permeability, \( \varepsilon \) (%) is the porosity, \( \mu \) (kg m\(^{-1}\) s\(^{-1}\)) is the viscosity and \( p \) (Pa) is the pressure.

The basic equations; mass, energy and species can be written following a general form:

\[
div(\varepsilon \rho U \Phi) = div(\Gamma \Phi \text{grad} \Phi) + S_{\Phi}
\]

where \( \varepsilon \rho \) (kg m\(^{-3}\)) is the density, \( \Phi \) is a general variable, \( \Gamma \Phi \) (m\(^2\) s\(^{-1}\)) is the diffusion coefficient and \( S_{\Phi} \) is the source term. Table 2 explains mass, energy and species equations obtained from the Eq. (5).

The fuel used is a gas mixture and based on the ideal gas law:

\[
PV = nRT
\]

(6)

where \( V \) (m\(^3\)) is the volume occupied by the fuel, \( n \) is the mols number, \( R \) (kg m\(^{-1}\) s\(^{-1}\)) is the gas constant and \( T \) (K) the temperature. The relation which gives the mole number is:

\[
n = \frac{m}{M}
\]

(7)

where \( m \) (kg) and \( M \) (kg mol\(^{-1}\)) are the mass and the molar mass respectively. As a result, the fuel density \( \rho_{\text{fuel}} \) can be expressed as (Hamid, 2010):

\[
\rho_{\text{fuel}} = \frac{P_{\text{fuel}} M_{\text{fuel}}}{RT}
\]

(8)

Where \( M_{\text{fuel}} \) is the fuel molar mass and it is calculated by the following relation (Hamid, 2010).

\[
M_{\text{fuel}} = \sum_{i=1}^{5} M_i X_i = M_{\text{CH}_4} X_{\text{CH}_4} + M_{\text{H}_2} X_{\text{H}_2} + M_{\text{CO}_2} X_{\text{CO}_2} + M_{\text{CO}} X_{\text{CO}} + M_{\text{H}_2\text{O}} X_{\text{H}_2\text{O}}
\]

(9)

<table>
<thead>
<tr>
<th>Components</th>
<th>Molar fractions</th>
<th>Refs.</th>
<th>Components</th>
<th>Molar fractions</th>
<th>Refs.</th>
</tr>
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<tr>
<td>CH₄</td>
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<td>Ferguson et al. (1996), Kang et al. (2009)</td>
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<tr>
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<td>CO</td>
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</tr>
<tr>
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<td>/</td>
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<td>H₂O</td>
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<td>Hu et al. (2008)</td>
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<td>H₂</td>
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<td>H₂O</td>
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<td></td>
<td>H₂O</td>
<td>0.284</td>
<td></td>
</tr>
</tbody>
</table>
where \( X_j \) is the molar fraction of the species \( j \).

So, the gas mixture density can be calculated by (Janardhanan et al., 2007; Hamid, 2010):

\[
\rho_{\text{fuel}} = \frac{P_{\text{fuel}}}{RT} (M_{\text{CH}_4}X_{\text{CH}_4} + M_{\text{H}_2}X_{\text{H}_2} + M_{\text{CO}_2}X_{\text{CO}_2} + M_{\text{CO}}X_{\text{CO}} + M_{\text{H}_2\text{O}}X_{\text{H}_2\text{O}}) \tag{10}
\]

Noting that the fuel specific heat is defined by (Bertin et al., 1981):

\[
C_{P_{\text{fuel}}} = \int_{T_1}^{T_2} \sum X_j C_{P_j} dT \tag{11}
\]

where \( C_{P_j} \) (J kg\(^{-1}\) K\(^{-1}\)) is the specific heat of species \( j \).

In the energy equation case, the general equation resolution requires the effective thermal conductivity expression \( \lambda_{\text{eff}} \) (W m\(^{-1}\) K\(^{-1}\)) and it can be calculated by the following formula (Zinovik and Poulikakos, 2009; Jiang and Chen, 2009; Pramuanjaroenkij et al., 2010):

\[
\lambda_{\text{eff}} = \varepsilon \lambda_{\text{fuel}} + (1 - \varepsilon) \lambda_{\text{sol}} \tag{12}
\]

where \( \lambda_{\text{fuel}} \) and \( \lambda_{\text{sol}} \) are the fuel and the solid thermal conductivity respectively.
The fuel dynamic viscosity is calculated by the following relationship (Hamid, 2010):

\[
\mu_{\text{fuel}} = \sum_{i} \mu_{i} X_{i} = \mu_{\text{CH}_{4}} X_{\text{CH}_{4}} + \mu_{\text{H}_{2}} X_{\text{H}_{2}} + \mu_{\text{CO}} X_{\text{CO}} + \mu_{\text{CO}_{2}} X_{\text{CO}_{2}} + \mu_{\text{H}_{2}O} X_{\text{H}_{2}O} + \mu_{\text{H}_{2}O} \frac{V_{\text{cell}}}{V_{\text{channel}}}
\]

(13)

For the mass sources, within the anode and the anode/electrolyte interface, the species mass source conservation equation ‘\(S_{i}\)’ is resulting from reforming reactions and electrochemical reactions. In this study, we are interested only in the mass source due to the reforming reactions; the steam reforming reaction ‘\(S_{\text{H}_{2}}\)’ and water gas shift reaction ‘\(S_{\text{H}_{2}}\)’ (Wang et al., 2009; Pramuanjaroenkij et al., 2010; Brus and Szymy, 2008; Iwai et al., 2010). The different mass sources expressions are shown in Table 3. At the cathode, the mass source is the result from oxygen consumption.

\[
S_{\text{O}_{2}, \text{in}} = \frac{M_{\text{O}_{2}}}{2F} I
\]

(14)

where ‘\(M_{\text{O}_{2}}\)’ (kg mol\(^{-1}\)), ‘\(I\)’ (A m\(^{-2}\)) and ‘\(F\)’ (C mol\(^{-1}\)) are the oxygen molar mass, the current density and the faraday’s constant.

In this study, the thermal source is the heat source due to the reforming reactions. So the heat source is due to the steam reforming reaction (\(S_{\text{H}_{2}}\)), which is an endothermic process and the water–gas shift reaction (\(S_{\text{H}_{2}}\)), which is an exothermic reaction. At the anode, the heat source is described by the following equation (Li et al., 2007; Ho et al., 2010; Kang et al., 2009; Wang et al., 2009; Nikooeyeh et al., 2007).

\[
S_{\text{an, in}} = S_{\text{r}} + S_{\text{s}}
\]

(15)

With

\[
S_{\text{r}} = -R_{\text{r}} \Delta H_{\text{r}}
\]

(16)

\[
S_{\text{s}} = -R_{\text{s}} \Delta H_{\text{s}}
\]

(17)

\(\Delta H\), \(\Delta H_{\text{r}}\) (mol m\(^{-3}\) s\(^{-1}\)) and \(\Delta H_{\text{s}}\) (J mol\(^{-1}\)) are the reaction rate and reactions enthalpy change (Ivanov, 2007; Brus and Szymy, 2008; Wang et al., 2009; Zinovik and Poulakakos, 2009).

- Reaction rate expressions

\[
R_{\text{r}} = k_{\text{r}}^{+} p_{\text{CH}_{4}} p_{\text{H}_{2}O} - k_{\text{r}}^{-} p_{\text{CO}} (p_{\text{H}_{2}})^{3}
\]

(18)

\[
R_{\text{s}} = k_{\text{s}}^{+} p_{\text{CO}} p_{\text{H}_{2}O} - k_{\text{s}}^{-} p_{\text{CO}} p_{\text{H}_{2}}
\]

(19)

Thus, the reaction’s rate constants \(k_{\text{r}}^{+}\) and \(k_{\text{r}}^{-}\) and the equilibrium constant are:

\[
k_{\text{r}}^{+} = 2169 \exp(-225103/RT)
\]

(20)

\[
k_{\text{s}}^{+} = 0.0183 \exp(-103842/RT)
\]

(21)

The \(k_{\text{r}}^{+}\) and \(k_{\text{s}}^{-}\) coefficients are determined based on the following equilibrium constants for both reactions.

\[
K_{\text{eq}} = \frac{k_{\text{r}}^{+}}{k_{\text{s}}^{-}}
\]

(22)

\[
K_{\text{eq}} = \frac{k_{\text{r}}^{+}}{k_{\text{s}}^{-}}
\]

(23)

\(K_{\text{eq}}\) and \(K_{\text{eq}}\) equilibrium constants can be calculated by the following empirical equations:

\[
K_{\text{eq}} = 1.0267 \times 10^{16} \exp(-0.2513Z^{4} + 0.3665Z^{3} + 0.5810Z^{2} - 27.134Z + 3.2770)
\]

(24)

\[
K_{\text{eq}} = \exp(-0.2935Z^{3} + 0.6351Z^{2} + 4.1788Z + 0.3169)
\]

(25)

\(Z\): is a variable depending on the temperature (Wang et al., 2009; Iwai et al., 2010; Amornchai et al., 2010).

\[
Z = \frac{1000}{T} - 1
\]

(26)

Reaction rate Eqs. (18,19) depend on the partial pressure. The ‘\(p_{j}\)’ of each species ‘\(j\)’ is equal to its mole fraction ‘\(X_{j}\)’ multiplied by the total pressure ‘\(P_{\text{fuel}}\)’ (Xi et al., 2007; Hamid, 2010).

\[
P_{\text{fuel}}: \text{The pressure mixture gas at the inlet channels.}
\]

The enthalpies change for the reforming reactions; steam reforming and water–gas shift are given by the following relations:

\[
\Delta H_{\text{r}} = 192.220 + 0.0541T - 2.062 \times 10^{-5}T^{2}
\]

(28)

\[
\Delta H_{\text{s}} = -44.034 + 0.00847T - 5.819 \times 10^{-7}T^{2}
\]

(29)

The fuel and air physical properties are shown in Table 4. The thermal conductivity, specific heat and the dynamic viscosity of species ‘\(j\)’ are polynomials of temperature of fourth order (CFD Fluent). There expressions are:

\[
\lambda_{j} = a + b T + c T^{2} + d T^{3} + e T^{4}
\]

(30)

\[
C_{p,j} = a + b T + c T^{2} + d T^{3} + e T^{4}
\]

(31)

\[
\mu_{j} = a + b T + c T^{2} + d T^{3} + e T^{4}
\]

(32)

Or, ‘\(a\)’, ‘\(b\)’, ‘\(c\)’, ‘\(d\)’ and ‘\(e\)’ are the empirical constants for each gas. The cell components physical property data are illustrated in Table 5.

<table>
<thead>
<tr>
<th>Source terms</th>
<th>CH(_{4})</th>
<th>H(_{2})</th>
<th>CO(_{2})</th>
<th>CO</th>
<th>H(_{2}O)</th>
</tr>
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<tbody>
<tr>
<td>(S_{r,j})</td>
<td>(0)</td>
<td>(3R_{s}M_{H}_{2})</td>
<td>(0)</td>
<td>(R_{s}M_{CO})</td>
<td>(-R_{s}M_{H}_{2}O)</td>
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<tr>
<td>(S_{s,j})</td>
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<td>(0)</td>
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<td>(R_{s}M_{CO})</td>
<td>(-R_{s}M_{H}_{2}O)</td>
</tr>
<tr>
<td>(S_{\text{eq},j})</td>
<td>(-R_{r}M_{CH}_{4})</td>
<td>((3R_{s} + R_{s})M_{H}_{2})</td>
<td>(R_{s}M_{CO})</td>
<td>((-R_{s} + R_{s})M_{H}_{2}O)</td>
<td></td>
</tr>
</tbody>
</table>
4. Results and discussion

The results of this study show the thermal fields of an AS_SOFC under the reforming reactions heat sources effect; the steam reforming reaction heat source effect, the water gas shift reaction heat source effect and the overall reforming reaction heat source effect. Inlet gas temperature and pressure are respectively 1273 K and 3 bars. This analysis is performed at four values (cases) of molar fractions’ inlet fuel respectively: (1) CH₄: 0.29, H₂: 0.09, CO₂: 0.01, CO: 0.01, H₂O: 0.6, (2) CH₄: 0.33, H₂O: 0.67, (3) CH₄: 0.01707, H₂: 0.2686, CO₂: 0.0491, CO: 0.024, H₂O: 0.4875 and (4) CH₄: 0.11, H₂: 0.258, CO₂: 0.228, CO: 0.057, H₂O: 0.254. The results are also discussed, following the AS_SOFC temperature elevation and abatement.

4.1. AS_SOFC thermal fields without heat source

Figs. 2 and 3(a and e) present the thermal fields without heat source effect; Sᵣ = 0. It is seen that heat transfer channels anode and cathode, warmer environment, to the other SOFC components (anode and cathode interconnections, the cathode, the anode and the electrolyte). For the first, third and fourth cases of fuel molar fractions cited above, the thermal field is constant and the minimum temperature value is 1272.92 K (Fig. 2(a) and Fig. 3(a and e)). In the second case of fuel molar fractions, the minimum temperature value is 1272.84 K which imposes a different distribution to the thermal fields (Fig. 2(e)).

4.2. AS_SOFC thermal fields with effect of steam reforming reaction heat source

Figs. 2 and 3(band f) present the thermal fields with effect of steam reforming reaction heat source; Sᵣ = Sr. For all the fuel molar fractions’ cases, the minimum temperature value is less than the field minimum temperature value without any heat sources. This minimum temperature is located in the anode far from the channels. Energy consumption is due to the steam reforming reaction endothermicity. This energy consumption is based on the methane percentage in the fuel. A greater methane (CH₄) percentage causes great energy consumption whereas a smaller methane percentage requires low energy consumption. So energy consumption is maximum in the second case of the fuel molar fractions (CH₄: 0.33, H₂O: 0.67), with a ΔT = −2.05 K.

4.3. AS_SOFC thermal fields with effect of water gas shift reaction heat source

Figs. 2 and 3(c and g) present the thermal fields with effect of water gas shift reaction heat source; Sᵣ = Sr. For the fuel molar fractions’ second case, the thermal field is unchanging. For other fuel molar fractions cases, an increase in the SOFC temperature is distinguished. This increase is located in the anode parts far from the canals. Energy production is due to the water gas shift reaction exothermicity. This energy production is based on the carbon monoxide (CO) percentage in the fuel. A greater carbon monoxide percentage causes a large power generation and a smaller carbon monoxide percentage requires low energy production. So, energy production is maximum at the fuel molar fractions’ fourth case (ΔT = 12.61 K) and it is minimum for the fuel molar fractions’ second case (ΔT = 0 K).

4.4. AS_SOFC thermal fields with effect of reforming reaction heat source

Figs. 2 and 3(dand h) present the thermal fields with reforming reaction heat source effect; Sᵣ = Sr + Sₛ. For the first and the second case of the fuel molar fractions, the reaction endothermicity gives a decrease in temperature. The minimum temperature is located at the anode far-away from gas channels (Fig. 2(dand h)). Energy consumption is maximum at the fuel molar fractions’ second case (Tₘᵢₙ = 1270.79 K and ΔT = −2.05 K). In contrast, for the fuel molar fractions’ third and fourth cases, a SOFC temperature increase is noted. The maximum temperature is focused in the anode away from gas channels (Fig. 3(d and h)). This energy production is created by the methane and carbon monoxide content in the fuel. Small methane percentage (third and fourth cases, CH₄: 0.01707 and 0.11), causes the dominance of the exothermic water gas shift reaction.

<table>
<thead>
<tr>
<th>Table 4</th>
<th>Fuel and air physical properties.</th>
</tr>
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<tbody>
<tr>
<td>Physical properties</td>
<td>Species</td>
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<tr>
<td>Mᵢ [g mol⁻¹]</td>
<td>16</td>
</tr>
<tr>
<td>Dᵢ [cm² s⁻¹]</td>
<td>Dᵢ = 0.364(Tᵢ⁰)⁻¹.⁵</td>
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</table>

<table>
<thead>
<tr>
<th>Table 5</th>
<th>Solid components’ physical properties.</th>
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<tbody>
<tr>
<td>Parameters</td>
<td>Anode</td>
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</tr>
<tr>
<td>ε [%]</td>
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<tr>
<td>λ [W m⁻¹ K⁻¹]</td>
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</tr>
<tr>
<td>γ [m]</td>
<td>2.10⁻⁴</td>
</tr>
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</table>

Kang et al. (2009), Zhan et al. (2006), Dokmaingam et al. (2010)
Table 6 contains the maximum and the minimum SOFC temperature ($T_{\text{max}}$, $T_{\text{min}}$) under different heat source influence and the temperature variation ($\Delta T$). The latter is the difference between the SOFC temperature value ($T_{\text{max}}$) under the heat source and the SOFC temperature without any heat source. The data show that the maximum temperature varies from 1272 to 1279 K, while the minimum temperature varies from 1270 to 1276 K. The temperature variation ($\Delta T$) ranges from 0.8 to 1.7 K. The graphs in Figures 2 and 3 illustrate the thermal fields for molar compositions of fuel under different conditions. The figures demonstrate the effect of the heat source on the temperature distribution within the SOFC.
source influence and the SOFC temperature value without heat source ($T_{\text{min}}$). The maximum and the minimum temperature variation values ($\Delta T$) are $-0.1$, 12.61 and 12.21 K and it is; ($-2.05$, 0 and $-2.05$ K) for heat sources due to the steam reforming, water gas shift reaction and the overall reforming reaction respectively. Temperature variation values; 1.38 and 12.21 K show the reforming reaction exothermicity at the fuel molar fractions’ third and the fourth cases when methane percent is low in the fuel.

For validation of results, the computed results are compared to our previous results (Abdenebi et al., 2011; Zitouni et al., 2013; Haddad et al., Oulmi et al., 2011) when the fuel is hydrogen and the chemical reaction is completely exothermic. Temperature field shows a temperature increasing around 10 K. In the present work when the fuel is methane, the chemical reactions studied are the reforming reactions; the steam reforming reaction, the water gas shift reaction and the overall reforming reaction. The temperature low order decrease is reasonable for the endothermic reaction at the SOFC plan studied.

On the one hand, our results are consistent with the mathematical model; the thermal fields under direct reforming reactions effect show a decrease or an increase in temperature value according to the endothermic or exothermic process (steam reforming reaction, overall reforming reaction and water–gas shift reaction). On the other hand, the temperature variation orders under direct reforming reactions are in the same interval as those obtained previously.

### 5. Conclusion

In this work, the thermal fields’ visualization of an AS SOFC is under inlet gas temperature and pressure values respectively; 1273 K and 3 bars. Results’ analysis shows that the reforming heat source effects are based on the inlet fuel molar fractions.

The steam reforming heat source effect is activated by the methane percentage. High methane content in the fuel requires high energy that is why the steam reforming effect appears.

The temperature decrease is maximum in the fuel molar fractions case when the methane percentage is dominant over the other fuel components ($\Delta T = -2.05$ K) and it is minimum in the fuel molar fractions case when the methane percentage is low ($\Delta T = -0.1$ K).

The water gas shift heat source effect is based on the carbon monoxide percentage. High carbon monoxide content causes an important energy production. As a consequence, the appearance of the water gas shifts the heat source effect. The temperature increase is maximal when the carbon monoxide percentage is highest, ($\Delta T = 12.61$ K, fourth case) and minimum when it is lowest ($\Delta T = 0$ K, second case).

### References


### Table 6: Temperatures and the temperature variations: $T_{\text{max}}, T_{\text{min}}, \Delta T$.

<table>
<thead>
<tr>
<th>Heat sources ($S_T$)</th>
<th>Molar fractions</th>
<th>1st Case</th>
<th>2nd Case</th>
<th>3rd Case</th>
<th>4th Case</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CH$_4$:0.29, H$_2$:0.09, CO$_2$:0.01, CO:0.01, H$_2$O:0.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$S_T = 0$</td>
<td>$T_{\text{max}}$</td>
<td>1273</td>
<td>1272.92</td>
<td>1273</td>
<td>1272.93</td>
</tr>
<tr>
<td></td>
<td>$T_{\text{min}}$</td>
<td>1272.92</td>
<td>1277.94</td>
<td>1273</td>
<td>1272.93</td>
</tr>
<tr>
<td></td>
<td>$\Delta T$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$S_T = S_s$</td>
<td>$T_{\text{max}}$</td>
<td>1273</td>
<td>1271.29</td>
<td>1273</td>
<td>1272.82</td>
</tr>
<tr>
<td></td>
<td>$T_{\text{min}}$</td>
<td>1270.79</td>
<td>1272.84</td>
<td>1273</td>
<td>1272.82</td>
</tr>
<tr>
<td></td>
<td>$\Delta T$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$S_T = S_r + S_s$</td>
<td>$T_{\text{max}}$</td>
<td>1273.52</td>
<td>1272.99</td>
<td>1273</td>
<td>1272.98</td>
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<tr>
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<td>$T_{\text{min}}$</td>
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<tr>
<td></td>
<td>$\Delta T$</td>
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</tr>
</tbody>
</table>


Kang, Ying-Wei, Li, Jun, Cao, Guang-Yi, Tu, Heng-Yong, Li, Jian, Yang, Jie, 2009. A reduced1D dynamic model of a planar direct internal reforming solid oxide fuel cell. J. Power Sources, 170–176.


