HYDROGEN CONSUMPTION AND POWER DENSITY IN A CO-FLOW PLANAR SOFC

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ABSTRACT

In the present work, power density and hydrogen consumption in a co-flow planar solid oxide fuel cell (SOFC) are studied according to the inlet functional parameters; such as the temperature, the pressure, the flow rates and the mass fractions of the species. Furthermore, the effect of cell size is also investigated.

The results of a zero and a one dimensional numerical electro-dynamic model show the remaining quantity of hydrogen at the output of the anode flow channel. The remaining hydrogen quantities and the SOFC’s power density obtained are discussed as a function of the inlet functional parameters, the geometrical configuration of the cell and for several cell voltages values imposed.

Keywords: Power density, Hydrogen consumption, IT-SOFC, electro-dynamic, mathematical modeling

1. Introduction

Fuel cells are electrochemical devices that convert directly the fuel chemical energy to electricity without the intermediate step of combustion. Hydrogen can be used both in conventional (combustion engines) and non-conventional devices (fuel cells) for electricity
production. Due to its high energy density is considered as the optimum choice for use in fuel cells. More precisely, solid oxide fuel cells (SOFCs) are receiving considerable attention due to flexibility in the fuel choice and the wide range of their applications. Moreover, SOFCs can operate directly on hydrocarbon fuels with or without internal reforming, thereby reducing the cost of an external reformer. Thus, fuel flexibility and cell performance are among the greatest advantages of SOFCs as compared to other types of fuel cells.

Electricity, heat and steam are the products of the hydrogen combustion. As it was previously mentioned, one of the electrochemical reaction applications are the SOFCs, where the fuel (hydrogen) and the oxidant (air) in the anode and in the cathode respectively diffuse through both electrodes towards the interface of the electrolyte anode where the steam is formed (Figure 1).

Various mathematical models have been developed for planar geometric configurations to solve transport equations (mass and heat) coupled with electrochemical processes to describe the reaction kinetics in SOFCs. Recently, a fully three-dimensional mathematical model for planar porous-electrode-supported PES-SOFC was developed in order to simulate the steady state electrochemical characteristics and the multi-species/heat transport for two types of PES-SOFC in the co-flow pattern [1]. Activation, ohmic, and concentration polarizations were considered. The Butler–Volmer equation, Ohm’s law, and Darcy’s gas model with constant porosity and permeability were used. Moreover, P. Asinari et al [2], performed numerical simulations for a thin anode (Ni-metal/YSZ-electrolyte cermet) for a high-temperature electrolyte supported SOFC. The three-dimensional numerical simulations show the spatial distribution of the mass fluxes for the reactants and the products of the electrochemical reactions. The described technique helps for the design of new improved materials and structures in order to statistically optimize these fluid paths. Jason Le Masters [3] developed a computational code in finite
differences, capable of executing preliminary conception calculations for the analysis of the thermal stresses which can take place in solid oxide fuel cells. The model operates in the stationary state conditions. The code was adapted to include significant changes concerning the structure the heat sources, the flow conditions and various properties of the fluids. The developed code was finally compared with the FLUENT commercial code. Eduardo Hernandez Pacheco [4] exposed an electrochemical thermal model which simulates the performance solid oxide fuel cell for operating conditions and different geometrical factors. The temperature, the current and the gas distribution were calculated in various areas. S. Valluru [5], in his work characterizes the thermal stresses during the fuel functioning cells with planar solid oxide fuel cell. The thermal stresses are calculated from the temperature fields by using ANSYS code. An analysis of the thermal stresses was implemented by two and three dimensional models. V.T. Srikar et al. [6] were interested in miniaturized cells SOFC. In their work they consider a planar configuration electrolyte supported by using a simple analytical model. The analysis of energy loss because of the heat conduction demonstrates the importance of the thermal insulation. This analysis with geometrical considerations, allows the identification of a structure which reduces simultaneously at least heat losses and assures sufficient stability. J. Yuan et al. [7], proceed to a three-dimensional numerical analysis of the gas flow and the thermal transfer in the anodic channel of a cell SOFC. They show that among the diverse parameters, the channel configuration and the properties of the porous anodic layer have significant effects as well on gas flow as on the thermal transfer. Masayuki Suzuki et al. [8], suggest a series of numeric simulations to see the influence of coupled transfers (heat and mass) with electrochemical reactions in a cell of the planar type SOFC. The results shows that the tension losses are mainly due to the internal resistance at the inter connector and the activation over potential in electrodes. It was also presented that the temperature difference in the cell becomes bigger when the length of the cell
increases. Based on the model results, they propose an improve conception of the cell, which uses a material of low electric resistance and high thermal conductivity. The tension calculated of the cell recently conceived is approximately 7 to 10 % higher than of the conventional cell. Moreover, the maximal temperature is reduced from 10 to 40 K. David L. and al. [9], studied the radiative transfer in electrodes and electrolyte, as well as radiative transfer between the fuel and the channels conveying the oxygen flow. The authors stated that the mode of radiative transfer was dominating and they study the heat losses by conduction. Y. Inui et al. [10] concentrate on the problem of the life of the ceramics used in cells SOFC and elucidate that the very high temperatures cause thermal stress in ceramics. The temperature distribution in the cell should be kept as constant as possible during the load operation. By considering this fact, the authors numerically optimize the operating parameters of the cell and the temperature of the admittance gas. Oosterkamp [11] mentions that the state of the art of the fuel cells development lays on the knowledge of the thermal transfers’ phenomena. K.J. Daun et al [12] show that due to the high operating temperatures, the radiative thermal transfer can play a significant role in the electrodes and the electrolyte layers of solid oxide fuel cells. They present a detailed characterization of the thermo physical properties of the composite materials, which are used to define a simple 2D model incorporating the characteristics of thermal transfer of the electrode and the electrolyte layers of a planar SOFC. Contrary to a certain literature published their results show that the thermal transfer by radiation has a negligible effect at the temperature field in these components and must not be adapted in the complete thermal models of planar SOFC.

In recent years, considerable progress has been made in modeling to improve the design and performance of this type of fuel cells. The objective of this paper is to study the dependence of the co-flow planar SOFC performance on its operating conditions (Figure 2-a). Several research works are conducted. Recently, Michael K.H. Leung [13] studied exchange current
density and effective diffusion coefficients related to the cell structural properties and the operating conditions. According to their findings, both the activation and the ohmic over potentials decreased significantly with increasing temperature. However, the concentration over potential was found to increase with increasing temperature. T. Tanaka et al [14] developed a three dimensional simulation code of the planar SOFC stack and the detailed effect of the radiation heat transfer was investigated. Relatively high voltage is obtained even when the ambient temperature is very low. Furthermore, the influence of the mixing ratio of hydrogen and carbon monoxide fuel on the SOFC performance through numerical simulations for a single cell plate of the co-flow type planar cell was studied by Y. Inui et. al [15]. According to the literature, few researches are devoted to the fuel qualities [16]-[23]. In the present investigation, the hydrogen consumed quantity in a co-flow planar SOFC was thoroughly examined (Figure 2-b). The effect of the cell operating parameters such as the temperature, the pressure, the flow rates, the mass fractions, thicknesses (electrodes and electrolyte) and the total cell length, on the hydrogen consumption were analyzed. The results of a zero and one dimensional (1-D) numerical study show the remaining quantity of hydrogen at the output of anode flow channel and the cell power density under the influence of the functional parameters and those relative to the geometrical configuration.

2. Mathematical modelling

Hydrogen fraction and the cell power density are calculated when the cell voltage is imposed by an electrical and a dynamic combined model. The voltage- current characteristic curves of a single co-flow cell are given by zero dimension models. Humidified hydrogen is fed to the anode flow channel of the SOFC. Through the anode flow channel, hydrogen quantity decreases because of its diffusion in the anode. At the anode flow channel output, a remaining
hydrogen quantity will be evacuated. Contrary to hydrogen that is consumed, the water quantity increases from the input to the output anode flow channel (Figure 3).

2.1. Hydrogen fraction in anode flow channel

In order to find the quantity of hydrogen in the anode flow channel, the mass balance of the fuel is applied. Also the mass balance for all the species of the anode flow channel is taken into consideration. The mass fraction of a species in an element of channel is calculated as follows (Figure 3).

\[
J_{\text{H}_2, \text{out}} = J_{\text{H}_2, \text{in}} - J_{\text{H}_2, \text{cons}}
\]  
(1)

Equation of continuity and conservation of mass in differential form are as follows:

\[
\begin{align*}
\frac{\partial (\rho, U)}{\partial x} &= 0 \\
\frac{\partial (\rho, U, X_k (x))}{\partial x} + \phi_k &= 0
\end{align*}
\]  
(2)

where \(k\) denotes the species: (\(\text{H}_2\), \(\text{O}_2\), or \(\text{H}_2\text{O}\)), \(U\) is the velocity, \(\rho\) is total density in flow channel, \(X(x)\): mass fraction of each species and \(\phi\) denotes the source term. In the present work, it characterizes the \(\text{H}_2\) mass consumption on the anode. It is expressed by:

\[
\phi_k = -\frac{jM_k}{nF}
\]  
(3)
where \( j \) is the cell current density and \( M \) the molar mass.

A mass balance applied to an element of the anodic flow channel at the entrance and at the exit of the channel is indicated respectively by \( (i) \) and \( (i+1) \) as it is shown in the following relation:

\[
X_k(i+1) = X_k(i) - \left( \frac{j M_k}{n F} \right) \left( \frac{1}{\rho_i \cdot Q_t} \right) \Delta x
\]  

(4)

The density and the molar mass total are given respectively by:

\[
\rho_t = \frac{p M_t}{T R}
\]  

(5)

\[
M_{t,an} = (X_{H_2} M_{H_2}) + (X_{H_2O} M_{H_2O})
\]  

(6)

\[
M_{t,ca} = (X_{O_2} M_{O_2}) + (X_{N_2} M_{N_2})
\]  

(7)

### 2.2 Current density

Considering all the overpotential effects in a SOFC, the external voltage (\( V \)) can be expressed as

\[
U_{cell}(j) = E_{Nernst} - \eta_{Ohm}(j) - \eta_{act,an}(j) - \eta_{act,ca}(j)
\]  

(8)

where \( E_{Nernst} \), \( \eta_{Ohm}(j) \), \( \eta_{act,an}(j) \) and \( \eta_{act,ca}(j) \) are the equilibrium voltage, ohmic overpotential, activation overpotential of the anode and activation overpotential at the cathode respectively.
In order to calculate the current density at every cell point, the previous equation is solved.

2.3 Equilibrium voltage

The equilibrium voltage can be expressed by the Nernst equation,

\[
E_{\text{Nernst}} = E^0(T) + \frac{R.T}{n.F} \ln \left( \frac{P^{0.5} X_{O2}^{0.5} X_{H2}}{X_{H2O}} \right) 
\]

where \( R \) is the universal gas constant (8.3145 J mol\(^{-1}\) K\(^{-1}\)), \( F \) the Faraday constant (96485 C mol\(^{-1}\)), \( T \) the absolute temperature, and \( X_{H2O} \), \( X_{H2} \) and \( X_{O2} \) are the mass fraction of steam, hydrogen and oxygen, respectively. Mass fractions \( X_k \) are functions of the cell current density \( j \). The reversible potential \( (E^0) \) can be expressed as:

\[
E^0(T) = -\frac{\Delta G(T)}{n.F} 
\]

where \( \Delta G \) is the standard Gibbs free energy of water formation and its expression is given by [24]:

\[
\Delta G(T) = \Delta H_r(T) - T \left\{ \Delta S^0_r + \int \frac{\Delta C_p(T)}{T} dT \right\} 
\]

\[
\Delta H_r(T) = \Delta H^0_r(T) + \int \Delta C_v(T) dT 
\]
\[ \Delta C_p = C_{pH_2O} - C_{pH_2} - 0.5C_{pO_2} \] 

The thermal capacity \( (Cp) \) is a function of the temperature \([25]\):

\[ C_p(T) = \sum_{i=1,6} a_i T^i \] 

### 2.4 Activation overpotential

The activation overpotential is related to the electrode kinetics at the reaction site. It represents the overpotential incurred due to the activation necessary for charge transfer. The electrode activation overpotential-current density relationship can be expressed by the Butler-Volmer equation:

\[ \eta_{act, an} (j) = \frac{R.T}{\alpha n_{an} F} \sinh^{-1} \left( \frac{j}{2j_{0,an}} \right) \] 

\[ \eta_{act, ca} (j) = \frac{R.T}{\alpha n_{ca} F} \sinh^{-1} \left( \frac{j}{2j_{0,ca}} \right) \]

where \( j_{0,i} \) is the exchange current density and the subscripts \( an \) and \( ca \) represent anode and cathode compartments, respectively. It should be noted that activation overpotential is very sensitive to \( j_0 \) values. It depends heavily on the electrode microstructure properties (i.e. porosity pore size) and operating conditions (gas composition, operating temperature and pressure). The exchange current densities depend on operational conditions and on the activation energy at the
anode and cathode, respectively. $E_{\text{act,an}}$ and $E_{\text{act,ca}}$. Their values are 140 KJ mol$^{-1}$ and 137 KJ mol$^{-1}$, respectively [26].

\[
\dot{j}_{0,an} = \frac{RT}{n_{an}F} \cdot K \cdot \exp\left(\frac{-E_{an}}{R \cdot T}\right)
\]  \hspace{1cm} (17)

\[
\dot{j}_{0,ca} = \frac{RT}{n_{ca}F} \cdot K \cdot \exp\left(\frac{-E_{ca}}{R \cdot T}\right)
\]  \hspace{1cm} (18)

2.5 Ohmic overpotential

According to Ohm’s law, the ohmic overpotential of the SOFC can be expressed in terms of the properties of the electrolyte by: where $e$ is the thickness of the electrolyte measured in (μm).

\[
\eta_{\text{Ohm}}(j) = R \cdot j
\]  \hspace{1cm} (19)

\[
R = \sum R_i
\]  \hspace{1cm} (20)

\[
R_i = \frac{e_i}{\sigma_i}
\]  \hspace{1cm} (21)

where $e$ is the thickness of the electrolyte measured in micrometers. Electrical conductivities expressions are expressed as follows [27]:

\[
\sigma_{\text{ac}} = \left( \frac{95.10^6}{T} \right) \exp\left( -\frac{1150}{T} \right) 
\] (22)

\[
\sigma_{\text{ca}} = \left( \frac{42.10^6}{T} \right) \exp\left( -\frac{1200}{T} \right) 
\] (23)

2.6 Power density

The cell power density is calculated by the following equation:

\[
P(j) = U_{\text{cell. } j} \tag{24}
\]

The cell power density is calculated for each 'j' value in any position along the fuel cell and for each imposed voltage.

3. RESULTS & DISCUSSION

In the present study, an electrodynamics model was developed in order to study the hydrogen consumption in a co-flow planar solid oxide fuel cell (SOFC). In a zero electrochemical model, the current density and power density are calculated for several imposed voltage. In a one dimensional dynamic model, hydrogen fraction is evaluated for several cell tensions operating. The result of this model analyses the effect of operational parameters (temperature, pressure, gas composition and rate flow) and cell size (cell long and thickness) to remaining hydrogen quantity at the out side of the anode channel and the cell power density. The remaining hydrogen in the flow channel and the cell power density mainly depend on all the parameters studied and presented in (Table 3).
3.1 Hydrogen consumption

3.1.1. H₂ mass fraction along the anode channel (U\text{cell} = 0.5 \text{ V})

The effect of the operating parameters and the geometric configuration of a SOFC on the hydrogen consumption at the anode flow channel is presented in Figure 4. The cell voltage was set equal to 0.5V, which corresponds to the maximum power density value. In this figure, one can see the effect of the operating temperature, pressure, flow rates, mass fractions of the species and cell size on H₂ mass fraction along the anode channel length about 0.1 m. As it can be seen, there is low H₂ consumption in the case of an electrolyte supported SOFC fed by humidified hydrogen (3%). The H₂ consumption is a function of temperature and as it can be observed more H₂ is consumed in higher temperature (T=1123K) due to the improved kinetics of the H₂ electro-oxidation and the increased diffusion coefficient from the feed stream to the electrolyte. Referring to the curves, when the air is used as oxidant, as the temperature increases, the H₂ consumption increases also. On the contrary at a cathode supported or an electrolyte supported SOFC as the pressure or the anode flow rate increases, the H₂ consumption decreases. The increasing in the cathode flow rate does not have an influence on the hydrogen mass fraction, which is in contrast to the effect of the anode flow rates.

3.1.2. H₂ consumption as a function of the operating cell voltage

The quantities of X_{H₂} at the exit of the anode flow channel are proportional to the opposite of the operating voltage (Figure 5). As it was showed in precedent figures, the parameters act in the same way. For the effect of temperature and the oxidant type, the hydrogen remaining quantities are proportional to those before these parameters’ effect (Figure 5, a,c). On the other hand, for temperature, pressure flow rate, SOFC cathode or electrolyte supported and SOFC
length, the hydrogen consumption is more important when it operates at low voltage. For higher voltage values, this difference is weaker (see Figure 5b, 5d, 5e and 5f). We speak about the increase in the consumption of hydrogen under effect of the increase of the pressure and the flow rate or reduction of the section of the channel. The pressure and the anode flow rate act equally on the dynamic and electric performance of the co-flow planar SOFC. Moreover, the quantity of hydrogen consumption, provide that these physical parameters must be multiplied by the same coefficient (see Figure 5b and 5e). At the highest cell voltage, these quantities remain low for all the geometric configurations. At medium cell voltage values, it is preferred anode supported SOFC to be used. At the electrolyte supported SOFCs highest values are at the anode exit channel are obtained (see Figure 5d). The remaining hydrogen quantities become lowest when SOFC length is larger (see Figure 5f).

3.2 Effect of operating parameters on SOFC power density

SOFC power density is a parameter that should be examined thoroughly in order to find the optimum operating conditions that enhance or decrease its value. As it can be obtained from the Figure 5 (a, b, d and e) the use of oxygen instead of the air, the increase in the operating pressure, temperature, flow (reduction in the section) or the geometrical configuration of the cell (i.e. anode supported) act positively on the value of the cell power density. In contrast, as it is shown in Figure 5f, as the cell length increases the H₂ consumption increases as well. However, the cell power density decreases with the cell length increment (1.6 Wcm⁻²). The cell power density in a cathode supported or electrolyte supported SOFC decreases too. More precisely, SOFC power density value is 1.04 Wcm⁻² and with electrolyte supported and just 0.23 Wcm⁻². This is attributed to the improved kinetics over a thicker electrode due to the fact that more active
sites are involved in the hydrogen oxidation. As it concerns the temperature increment, as it was previously mentioned enhances the H$_2$ consumption leading to higher power density values. (see Table 3-4). In table 3, one can see that the maximum power density values obtained in the present simulation study are with SOFC operating at high temperature (2.31 Wcm$^{-2}$). The use of pure oxygen or increasing the pressure in the flow channels has also important impact. Anode flow rate acts positively at the cell power density values. Under the effect of temperature, pressure, flow rate, channel length at an anode supported SOFC and the use of pure oxygen, the power density increases. This is due to physical phenomena that take place in the electrochemical system. In opposite, although that the H$_2$ consumption increase (pure O$_2$, temperature) (see Figure 5, a, c and f) or decrease (pressure, flow rate/ channel section), the power density value increase (see Figure 5, b, e).
4. CONCLUSIONS

In this present study, an electrodynamics model was developed to study the hydrogen consumption in a co-flow planar solid oxide fuel cell (SOFC). In a zero electrochemical model, the current density and power density are calculated for several imposed cell voltage. Moreover, a one dimensional dynamic model was developed in order to evaluate the hydrogen fraction across the anode flow channel. At the exit of the anode flow channel, the remaining hydrogen quantity and the cell power density are thoroughly examined and discussed according to the operating parameters (such as the temperature, the pressure, the flow rates) and the cell size (cell length, electrode and electrolyte thickness). According to the model predictions, the remaining hydrogen quantity and the cell power density mainly depends on all the above studied parameters as follow:

1- A higher power density value and a low H₂ consumption are obtained with high pressure values and with high flow rates.

2- Higher power density values and a higher H₂ consumption are obtained with the temperature increment and with the use of pure oxygen at the cathode side.

3- In opposite, a lower power density value and a higher H₂ consumption are obtained with increasing the length.

4- Both power density and H₂ consumption decrease when the SOFC is cathode or electrolyte supported.
## Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T$</td>
<td>temperature, (K)</td>
</tr>
<tr>
<td>$j$</td>
<td>current density, (A.m$^{-2}$)</td>
</tr>
<tr>
<td>$j_0$</td>
<td>exchange current density, (A.m$^{-2}$)</td>
</tr>
<tr>
<td>$R$</td>
<td>universal gas constant, (J.mol$^{-1}$K$^{-1}$)</td>
</tr>
<tr>
<td>$\eta$</td>
<td>overpotential, Volt</td>
</tr>
<tr>
<td>$p$</td>
<td>pressure (Pa)</td>
</tr>
<tr>
<td>$F$</td>
<td>Faraday’s constant (C mol$^{-1}$)</td>
</tr>
<tr>
<td>$X$</td>
<td>Molar fraction (%)</td>
</tr>
<tr>
<td>$J$</td>
<td>mass flow (mol s$^{-1}$)</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>electrical conductivity, ($\Omega^{-1}$m$^{-1}$)</td>
</tr>
<tr>
<td>$C_p$</td>
<td>molar heat capacity, (J.mol$^{-1}$K$^{-1}$)</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>thermal conductivity, (Wm$^{-1}$ K$^{-1}$)</td>
</tr>
<tr>
<td>$\Delta H$</td>
<td>enthalpy (J.mol$^{-1}$)</td>
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<tr>
<td>$\Delta S$</td>
<td>entropy, (J.mol$^{-1}$K$^{-1}$)</td>
</tr>
<tr>
<td>$\phi$</td>
<td>heat source, (W m$^{-3}$)</td>
</tr>
<tr>
<td>$\rho$</td>
<td>gas density, (kg m$^{-3}$)</td>
</tr>
<tr>
<td>$M$</td>
<td>mass molar (kg mol$^{-1}$)</td>
</tr>
<tr>
<td>$e$</td>
<td>Thickness (m)</td>
</tr>
<tr>
<td>$ca$</td>
<td>cathode</td>
</tr>
<tr>
<td>$elec$</td>
<td>electrolyte</td>
</tr>
<tr>
<td>$r$</td>
<td>reaction</td>
</tr>
<tr>
<td>$cell$</td>
<td>cellule</td>
</tr>
<tr>
<td>$0$</td>
<td>standard (25°)</td>
</tr>
</tbody>
</table>

### Subscripts and Superscripts

- Ohm: Ohmic
- act: activation
- cons: consommé
- t: total
- an: anode
References


Figure captions

Figure 1. Mass transfer in SOFC anode flow channel

Figure 2. Co-flow planar SOFC components. (a): Anode channels (b): calculation field

Figure 3. Hydrogen balance mass through P1 plan

Figure 4. Hydrogen quantity through anode channel (Ucell=0.5 V): Effect of operating parameters and geometric configuration

Figure 5. XH2 quantities at the output anode channel and the power densities for several operating voltage. Effect of operating parameters and geometric configuration
Table 1: Parameters values. [12] - [15]

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Parameters</th>
<th>Value</th>
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<tbody>
<tr>
<td>$S_{ca}$</td>
<td>2x3</td>
<td>$X_{O_2}$</td>
<td>0.21</td>
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<tr>
<td>$S_{an}$</td>
<td>(2x2.5)</td>
<td>$X_{H_2}$</td>
<td>0.97</td>
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<td>$Q_a$</td>
<td>$7.9 \times 10^{-8}$</td>
<td>$X_{H_2O}$</td>
<td>0.03</td>
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<tr>
<td>$Q_c$</td>
<td>$4.4 \times 10^{-7}$</td>
<td>p</td>
<td>$1.01310^5$ (N.m$^{-2}$)</td>
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<tr>
<td>$\Delta H_r^0$ (H$_2$O)</td>
<td>$-242 \times 10^3$</td>
<td>T</td>
<td>1023 K</td>
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<tr>
<td>$\Delta S_r^0$ (H$_2$O)</td>
<td>$-44.4$</td>
<td>F</td>
<td>96320 (C.mol$^{-1}$)</td>
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<td>$K_{ca}$</td>
<td>$2.35 \times 10^{11}$</td>
<td>$\alpha$</td>
<td>0.5</td>
</tr>
<tr>
<td>$K_{an}$</td>
<td>$6.54 \times 10^{11}$</td>
<td>$L_{channel}$</td>
<td>0.1 (m)</td>
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<td>$E_{ca}$</td>
<td>137000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$E_{an}$</td>
<td>140000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\sigma_{el}$</td>
<td>$1.04 \times 10^{-2}$</td>
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Table 2: Electrode and electrolyte thickness

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<tr>
<th>Thickness</th>
<th>$e_{\text{an}}$</th>
<th>$e_{\text{ele}}$</th>
<th>$e_{\text{ca}}$</th>
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<tbody>
<tr>
<td>Anode supported</td>
<td>500</td>
<td>10</td>
<td>50</td>
</tr>
<tr>
<td>Cathode supported</td>
<td>50</td>
<td>20</td>
<td>300</td>
</tr>
<tr>
<td>Electrolyte supported</td>
<td>50</td>
<td>150</td>
<td>50</td>
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Table 3: H₂ fraction at the output of anode channel and maximal power density for $U_{\text{cell}}$ maximal values.

<table>
<thead>
<tr>
<th>Physics parameters</th>
<th>$U_{\text{cell}}$ (Volt)</th>
<th>H₂ Output (%)</th>
<th>$P_{\text{max}}$ (Wcm⁻²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxidant: Air / O₂ pure</td>
<td>0.50</td>
<td>0.931</td>
<td>1.80</td>
</tr>
<tr>
<td>Pressure: (p= 2p)</td>
<td>0.50</td>
<td>0.945</td>
<td>1.80</td>
</tr>
<tr>
<td>Temperature (T=1023-1123 K)</td>
<td>0.56</td>
<td>0.923</td>
<td>2.31</td>
</tr>
<tr>
<td>Anode supported (AS)</td>
<td>0.50</td>
<td>0.932</td>
<td>1.68</td>
</tr>
<tr>
<td>Cathode supported (CS)</td>
<td>0.56</td>
<td>0.945</td>
<td>1.04</td>
</tr>
<tr>
<td>Electrolyte supported (ES)</td>
<td>0.68</td>
<td>0.963</td>
<td>0.23</td>
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<tr>
<td>Flow rate (Qan)</td>
<td>0.50</td>
<td>0.946</td>
<td>1.74</td>
</tr>
<tr>
<td>Cell length (L)</td>
<td>0.50</td>
<td>0.912</td>
<td>1.60</td>
</tr>
</tbody>
</table>

• Standard*: Standard case is characterized by air as oxidant and the geometric configuration is anode supported SOFC.
Table 4: Effect of increasing parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>$X_{O2}$</th>
<th>T</th>
<th>L</th>
<th>p</th>
<th>Q</th>
<th>AS</th>
<th>CS</th>
<th>ES</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X_{H2}$ (% outlet)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>$X_{H2}$ consumption (%)</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$P$ ($W.cm^{-2}$)</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

+: increasing, -: decreasing
Figure 1: Mass transfer in SOFC anode flow channel
Figure 2: Co-flow planar SOFC components
(a): Anode channels (b): calculation field
Figure 3: Hydrogen balance mass through P1 plan

\[ \text{Anode canal} \]

\[ \text{CEA SOFC} \]

\[ \text{Cathode canal} \]

\[ \text{1 element} \]

\[ \text{1 canal} \]

\[ \text{In} \quad J_{O_2, \text{in}} \quad J_{O_2, \text{out}} \quad J_{H_2O, \text{out}} \quad \text{Out} \]

\[ \text{Out} \quad J_{O_2, \text{Out}} \]
Figure 4: Hydrogen quantity through anode channel (Ucell=0.5 V).

Effect of operating parameters and geometric configuration
Figure 5: $X_{H2}$ quantities at the output anode channel and the power densities for several operating voltages. Effect of operating parameters and geometric configuration.

(a): $X_{O2}$ (air/O2)

(b): Pressure

(c): Temperature

(d): Electrode and electrolyte thickness

(e): Flow Rate

(f): Cell Length

Voltage. Effect of operating parameters and geometric configuration.