A Two-Dimensional Numerical Study on the Effect of Radiation and Polarization Losses on the Temperature Distribution in a Solid Oxide Fuel Cell Anode

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Abstract

High operating temperature of solid oxide hydrogen fuel cell electrodes (SOFCs) is mainly due to energy losses due to different polarization phenomena, represented by ohmic, concentric and activation polarizations. These polarizations lead to the generation of radiative phenomena in SOFCs. In this work, various phenomena of heat transfer by radiation are included, and then discuss the challenges that still exist in understanding, predicting and quantifying the effects of radiation in SOFC materials and systems. This can be done in one of two ways, either through experimental or numerical studies. Although, these phenomena witness a complexity due to their relation to the thermal aspect in addition to the electrochemical aspect, we concluded through the results of this research, according to the numerical treatment method of the resulting equations, that the presence of the values of the radiation limit never changes the temperature distribution field at the level of these poles. Hence, it is possible to neglect the effect of heat transfer by radiation on anode of a SOFC cell.

Keywords: Radiation, Ohmic, Temperature, Activation, polarizations, Modeling, Anode.

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1. Introduction

Solid oxide fuel cell (SOFC) is among the electrochemical devices that directly convert, by converting chemical energy into electrical energy. As this process is considered one of the most efficient operations, it is also considered one of the effective practical methods that allow reducing environmental problems. Perhaps the most prominent of these are greenhouse gas emissions, air pollution and climate change. SOFCs also have many qualities that qualify them to be at the fore in attracting researchers' interest to benefit from and use them in several fields; this is due to their high efficiency, modularity, good fuel adaptability, smooth operation, low maintenance needs and high reliability. SOFCs are developed and manufactured to operate mainly in the temperature range from 900 to 1000 °C. The occurrence of high operating temperatures at the electrodes of SOFCs is mainly due to the different polarization losses that occur in it, represented in ohmic, activation and concentration, this is what gave rise to radiological phenomena in SOFCs.

Many researchers have investigated in detail the importance of thermal radiation inside SOFCs that are characterized by medium temperature, for example, what happens during thermal radiative transfer between the PEN and the separation board, which is somewhat similar to the method of the current study [1,2]. Although, the Molten carbonate fuel cells (MCFC) stack has been calculated and taken into account. The great interest of researchers in radiological phenomena is demonstrated by the work presented by (Costamagna and Honegger [3], Alimi et al., [4] and Damm and Fedorov [5]).

A more detailed radiation model has also been studied by (Yakabe et al. [6] and Russner et al. [7]). The proposed study of surface radiation modeling was also done by Sanchez where the simplified radiation model incident between parallel walls was compared with another model, which is more complex, including oblique radiation [8, 9]. In spite of all this, they found that surface-to-surface radiation modeling is often relied upon using rather simple radiation models, to be calculated as the fatigue of the net radiative heat exchange occurring between the SOFC surfaces and the black container [10-12]. Or, as in the work of (Xue et al. [13] and Alhazmi et al. [14]) where is extracted as the net heat exchange incident between infinite parallel gray reciprocal walls.

Among the studies that concerned on the study of the importance of the radiative heat transfer process was by (Damm and Fedorov [5]), followed by the study of (Daun et al. [15], Digiuseppe [16], and Murthy and Fedorov [17]).

In addition, a study was presented on the effects of thermal radiation numerically and by comparing all cases with or without radiant heat transfer [18]. On the other hand, the design of tubular SOFC temperature dynamics was addressed by (Zhang et al. [19], and Mustafa et al. [20]). This study was done in one dimension and then it was to address conduction, convection and radiation. It is remarkable that most researchers ignored radiation heat absorbed by the fuel and air flow [21-24]. In another study, given that the channels were considered rather thin, Ma neglected the effects of radiative heat transfer, as the cells were about the same temperature [25].

In addition, and in order to simplify further the matter; the effect of thermal radiation was not taken into account during the process of forecasting the temperature of the fuel cell [26], as these models can deviate in their accuracy and reliability of their results as a result of their imposed limits [18].

The topic of current work is limited to the relative importance of radiation in SOFCs; its purpose is to give detailed information about the heat radiation inside the different parts of the SOFC (anode, cathode, electrolyte and interconnection). A simple investigation was carried out to check whether thermal radiation was needed or not, since our calculation is based on all the data taking into account the medium temperature anode and the supported SOFCs. The ultimate objective of this paper is to identify and highlight the importance of radiative heat transfer phenomena occurring at the anode of typical planar SOFCs.

2. Radiation Phenomena in SOFC

The SOFC is considered among the high temperature devices, and although the variation in temperature values within the lanes may be small, they are considered present values and therefore radiative heat transfer will exist.

Logically, the presence of radiation has an important role within the gas channels, as well as the electrolyte-electrode group, and in the process of using thermal insulation layers. Some of these issues are highlighted by Beale [27]. The surface-to-surface radiation ($q^{\cdot}\_k$) in microchannels could be calculated by using the grid method [28]. The equations governing the radiation phenomenon were used to determine the temperature distribution at the anode.

$$\dot{q}_k = \frac{\sigma T_k^4 - q_{0k}}{\left(\frac{1-\varepsilon_k}{\varepsilon_k A_k}\right)} = \sum_{j=1}^{N} \frac{q_{0j} - q_{0k}}{\left(\frac{1}{F_{k-j}}\right) A_k} \quad (1)$$

σ = Stefan–Boltzmann constant $(JK^4\ m^2\ s^{-1})$
T = Temperature (K)
q_{0k} = Radiosity (W)
ε_k = Emissivity of boundary
A_k = area (m^2)
F_{k-j} = Configuration factor

Due to our adoption during the construction of a network of resistors, in this case, we can eliminate the unknown radiation and then solve the system of equations. Because the small channels used are rather narrow, in this case there will only be a certain number of direct neighbors (opposite and two sides) in any given channel, and then the calculation can be simplified perfectly. Perhaps calculating surface-to-surface radiation along the channel is an additional, unjustified chore. Yakabe et al. [6] describes a procedure for performing the calculation of surface radiation in gaseous microchannels, the latter of which is quite different from the standard analysis, Equation (1). According to the researcher (Xie and Xue [28]), he found that surface-to-surface radiation can affect the temperature until it reaches (25–50 K) [28].

Although the preparation of gas channels is analytically simplified, we find that the electrolytes and possibly the SOFC electrodes constitute radiative sharing media.

Murthy and Fedorov [17] introduced the idea of excluding all effects of radiation in the co-electrolyte that could lead to over-prediction of temperatures as high as (100-200 K) if electrolyte supported SOFC was used [18]. These discrepancies indicate that there is a need to include the effects of radiation at present, although the idea is still disputed.

Other researchers [18] put forward the hypothesis that the electrolyte we can control and manipulate as optically thin, while we can regard the electrodes as optically thick.

We were able to collect some empirical data to support this thesis, despite the scarcity of the data. However, [5,15] suggested the idea that the electrodes would be optically thick enough to be completely opaque for all practical purposes. The general problem with radiative heat transfer lies in the medium involved in 'distance' heat transfer, which is described mathematically by a differential integral equation called Radiative Transfer Equation (RTE). For the isotropic gray scattering medium, we can write the latter in simplified form as follows [29, 30].

$$\underbrace{\frac{di}{ds}}_{(1)} = \underbrace{-(a-\sigma_s)i}_{(2)} + \underbrace{a\frac{\sigma T^4}{\pi}}_{(3)} + \underbrace{\frac{\sigma_s}{4\pi}.\int_{\omega=0}^{4\pi} i d\omega}_{(4)} \qquad (2)$$

The terms in Equation (2),

(1) : Change in intensity

(2) : Absorption and out scattering

(3) : Emission

(4) : In scattering

where,

i = radiation intensity $(W/sr.m^2)$

s = displacement

a = absorption coefficient(m^{-1})

σ_s = scattering coefficient (m^{-1})

ω = solid angle

3. Mathematical modelling

The fuel cell stack is divided into several computational fields by using field decomposition with each cell treated as a separate process Figure 1 [31].

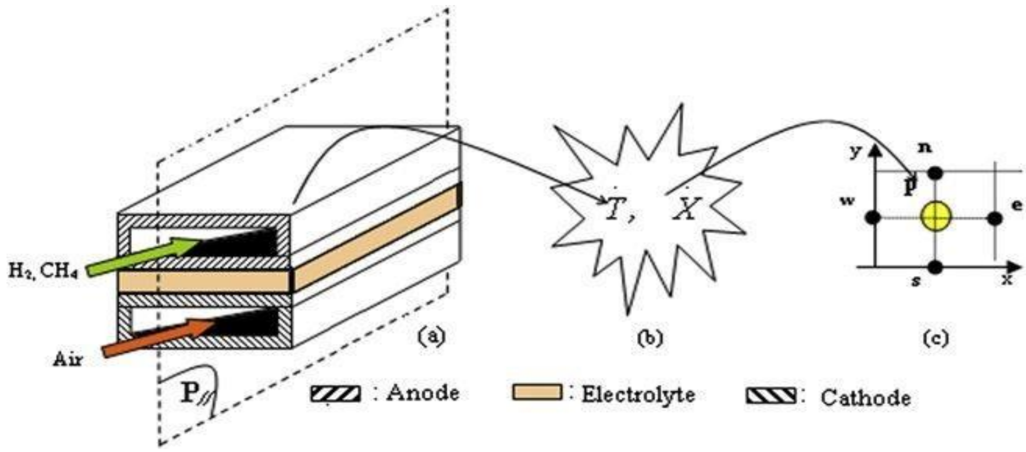

Fig. 1:(a): Domain decomposition for a cell stack. (b): Gas channel control volume for mass and temperature conservation. (c): study point

After solving Equation (2), we can use the spectral density of radiation in order to calculate the radiant heat flux at any point inside the medium. In order to calculate the temperature contained within the SOFC, we must add with the radiation the total energy equation; then it is simplified into two dimensions. (x, y) [12]. The prototype equation having the following form:

$$\underbrace{\rho C_p \frac{d\phi}{dt}}_{accumulation\ term} + \underbrace{\frac{\partial}{dx}(\rho C_p u\phi) + \frac{\partial}{dy}(\rho C_p v\phi)}_{convectif\ term} = \underbrace{\frac{\partial}{dx}\left(\left(k_{eff,c} + k_R\right)\frac{\partial \phi}{\partial x}\right) + \frac{\partial}{dy}\left(\left(k_{eff,c} + k_R\right)\frac{\partial \phi}{\partial x}\right)}_{diffusion-radiation\ term} + S_T \quad (3)$$

where,

ρ = Density (kgm^{-3})

C_p = Specific heat $(J\ kg^{-1}\ K^{-1})$

ϕ = Scattering phase function

t= Time (s)

$u\ ,v$ = Velocity components $(m\ s^{-1})$

$k_{eff,c}$ = Effective thermal conductivity coefficient of the cathode.

where k_R is the Rosseland radiative conductivity and defined as $k_R = \frac{16n^2\sigma T^3}{3\beta_R}$ [24]. S_T is the total volumetric heat sources which occurs in the electrodes. They can be classified, respectively, as an Ohmic heat source, an activation heat source and an entropy heat source Q_{Ohm}, Q_{act}, Q_{con} ; and we can list the terms of radiation phenomena at the anode and cathode according to Table 1.

where,

n = Refractive index of medium

β_R = Extinction coefficient of the medium

Table 1: Heat sources terms used in simulation [31]

Parameter	Anode	Cathode
Electric conductivity $(\Omega^{-1}.m^{-1})$	$\frac{95.10^6}{T}\exp\left(-\frac{1150}{T}\right)$	$\frac{42.10^6}{T}.\exp\left(-\frac{1200}{T}\right)$
Ohmic source $(W.m^{-3})$	$\frac{j^2}{\sigma_{ele,\ a}}$	$\frac{j^2}{\sigma_{ele,\ c}}$
Activation source $(W.m^{-3})$	$\frac{RT}{\alpha nF}\ln\left(\frac{j}{i_{0,a}}\right)j$	$\frac{RT}{\alpha nF}\ln\left(\frac{j}{i_{0,c}}\right)j$
Exchange current Density $(A.m^{-2})$	$\gamma_a L_{TPB}\left(\frac{P_{H_2}P_{H_2O}}{P_{ref}^2}\right).\exp\left(-\frac{E_{act,a}}{RT}\right)$	$\gamma_c L_{TPB}\left(\frac{P_{O_2}}{P_{ref}}\right)^{0.25}\exp\left(-\frac{E_{act,c}}{RT}\right)$
Concentration Source $(W.m^{-3})$	$\left(-\frac{T\Delta S_a}{4F}\right)i$	$\left(-\frac{T\Delta S_c}{4F}\right)j$
Entropy $(J.K^{-1})$	$2S_{H_2O} - S_{H_2} - 2S_{O^{2-}} + 4S_{e^-}$	$2S_{O^{2-}}\text{-}S_{O_2} - 4S_{e^-}$
Radiation source $(W.m^{-3})$	$-\nabla q_{r,a}$	$-\nabla q_{r,c}$

According to Anode:

$$\underbrace{\rho C_p \frac{dT}{dt}}_{accum\ term} + \underbrace{\frac{\partial}{dx}\left(\left(\rho C_p u\right)_{fuel} T\right) + \frac{\partial}{dy}\left(\left(\rho C_p v\right)_{fuel} T\right)}_{conv\ term}$$
$$= \underbrace{\frac{\partial}{dx}\left(\left(k_{eff,a} + k_{R,a}\right)\frac{\partial T}{\partial x}\right) + \frac{\partial}{dy}\left(\left(k_{eff,a} + k_{R,a}\right)\frac{\partial T}{\partial x}\right)}_{diffus-radia\ term} + S_T \quad (4)$$

where,

$k_{eff,a}$: Effective thermal conductivity coefficient of the anode.

In order to assess the effect of different losses, and radiation on the SOFC temperature distribution process, the simulation conditions are summarized and listed in Tables 2 and 3.

Table 2: Conditions and parameters for simulation [31].

Parameter	Value
Fuel inlet temperature, (K)	800
Oxide inlet temperature, (K)	800
Pressure, (Pa)	1
Cathode flow channel (Air), (N m3 s^{-1})	4.4×10^{-7}
Anode flow channel (Fuel), (N m3 s^{-1})	7.9×10^{-7}
Air dynamic viscosity, (m2.s-1)	2.3×10^{-7}
k, Thermal conductivity of anode Ni-YSZ (W m-1 K^{-1})	2
k, Thermal conductivity of cathode, LSM (W m-1 K^{-1})	2
a, absorption coefficient (m^{-1})	0.5
j_0, Electrode exchange current density (A.m-^{2})	0.002
γ, Coefficient for the exchange current density	0.04
Ea Activation energy	$J\ mol^{-1}$
S_T the total volumetric heat sources	$W.m^{-3}$

Table 3: Geometry parameters of the planar SOFC [31] .

Component	Value
Anode thickness	500 μm
Electrolyte thickness	10 μm
Anode channel height	50 μm
Cathode channel width	2.5 mm
Cathode thickness	2.5 mm
Anode channel width	2.5 mm
Cathode channel height	500 μm
Cell length	100 mm

4. Results and Analysis:

Various losses are important parameters affecting the temperature distribution of an anode supported SOFC. Figures (2, 3 and 4) show the results of the temperature distributions at the anode side and specifically for the middle cell. It is thought that both the fuel and the airflow are both heated up but gradually that is because of the entropy changes in heat generation during the electrochemical reaction at the anode-electrolyte interface.

Because of the large resistive force in the anode channel, we found the fuel mass flow rate to be rather weak and its velocity was also very low especially in the porous medium.

The results for an illustration of the thermoelectric model show the influence of different polarization losses on the SOFC anode. This is, obviously, according to the generation term in Equation (4), the latter reflects the source of heat which is mainly caused either on the one hand by the entropy change of the electrochemical reaction or on the other hand from the Joule effect.

When moving from the inlet to the gas outlet, i.e. in the previous three study cases, we find that the increase in temperature is due to the irreversible processes occurring on the surface of the electrodes (chemical, activation) as well as the Joule effect at the electrode.

We note that during the first case, the maximum temperature rises until it reaches 1000 K, while in the second case, which is the state of activation, it nears, 1053.33 K. It is also noted that the Ohmic effect generates a hot region near the middle cell of the stack, while the temperature takes its highest value, which is estimated at 1106.66 K compared to the previous case. Table 4 presents the maximum temperature (K), for the different cases in the Anode middle.

Table 4: The maximum temperature (K), for the different cases in the Anode middle.

Anode middle	With chemical polarization	With activation polarization	With Ohmic polarization	Radiation effect
T (K)	1000	1053.33	1063.33	1063.33

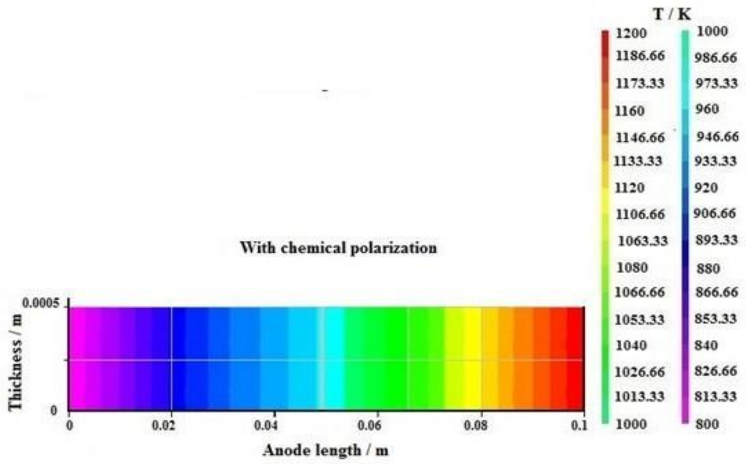

Fig. 2. Chemical polarization effect on the temperature distribution.

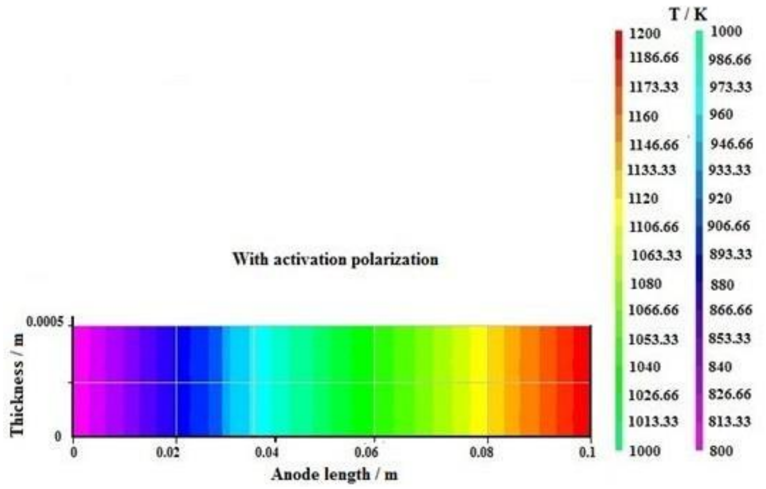

Fig. 3. Activation polarization effect on the temperature distribution.

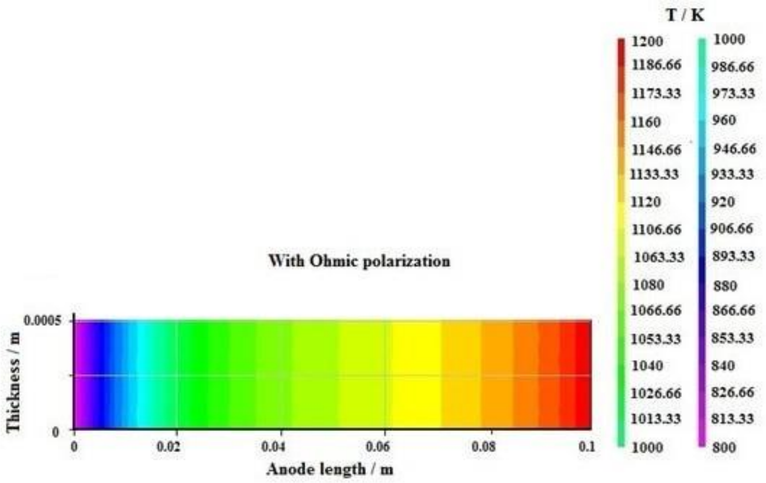

Fig. 4. Ohmic polarization effect on the temperature distribution

In addition to the term radiation, and as Rosland predicted, the term radiant heat; we find that the simulation result obtained in Figure 5, which displays the temperature variation of the liquid medium manifested in it. The use of conductivity was also used to explain the effects of radiation on the optically thickened Ni-YSZ and LSM electrodes.

The obtained result is similar to that obtained in the previous cases. We note that the heat generated by exothermic radiation has a weak effect on the temperature distribution process. The maximum values of the temperature of the middle of the anode reached about 1106.66 K (see Table 4).

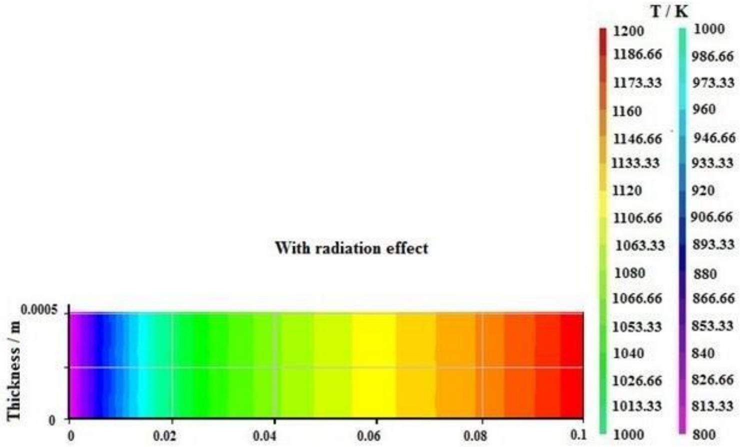

Fig. 5. Radiation effect on the temperature distribution.

5. Conclusions

In the present work, it is found that the temperature distribution diffuses towards the parallel plane and according to the direction of the gas flow, taking into account the effect of the different, previous polarization losses represented in ohmic polarization, activation polarization as well as concentration polarization that leads to the emergence of radiative phenomena within SOFCs.

A numerical two-dimensional planar model of the SOFC was developed, which is related to the heat transfer of thermal radiation according to the overall energy conservation equation by means of the local radiative flux divergence.

For this purpose, a numerical analysis of the anode was carried out in order to estimate the temperature change. The current developed model was then successfully used to simulate and analyze four states: chemical, activation, ohm and radiation. For all the previous cases, we did not find an effect of radiation phenomena on the temperature distribution, compared to other losses according to previous published results.

After simulation and analysis of this developed model, both with and without radiation; a prototype of a medium-temperature SOFC process, through which it was demonstrated that it is an indicative and useful tool for accessing information about the radiation forcing rate in a SOFC. However, the presence of the term radioactive source does not change the value of the temperature distribution; this led to neglect the effects of heat transfer by radiation on the temperature distributions in the SOFC. Hence, despite the effect of radiation, they are not considered important in estimating how the temperature distributions inside the cell are. In addition, the present model demonstrated that the radiation effect at the SOFC anode was very small and could be completely neglected. Modeling radiative heat transfer in SOFC is a complex practical method, and one must be armed with a good knowledge of phenomenological properties, such as absorption coefficient, scattering coefficient, reflectivity, emission refractive index, … etc. Therefore, these trends must be verified in any future work so that more accurate radiological models must be used.

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