

Radiation Heat Transfer Effect in Solid Oxide Fuel Cell: Application of the Lattice Boltzmann Method

Imen Mejri, Ahmed Mahmoudi, Mohamed A. Abbassi, Ahmed Omri

Abstract—The radiation effect within the solid anode, electrolyte, and cathode SOFC layers problem has been investigated in this paper. Energy equation is solved by the Lattice Boltzmann method (LBM). The Rosseland method is used to model the radiative transfer in the electrodes. The Schuster-Schwarzschild method is used to model the radiative transfer in the electrolyte. Without radiative effect, the found results are in good agreement with those published. The obtained results show that the radiative effect can be neglected.

Keywords—SOFC, lattice Boltzmann method, conduction, radiation.

I. INTRODUCTION

SOLID OXIDE FUEL CELL (SOFC) operates at elevated temperature producing heat which can be used for heating purposes or for feeding gas turbines to produce more power. Fuel cells have been attracting more attention in the search for new efficient and eco-friendly energy sources for future. Because of their high operating temperatures (typically 800–1200K), thus, radiation heat transfer must be given special consideration in thermal modeling efforts, including stack thermal management and materials development. During the last decades many papers have reported results of numerical calculations, some including the effects of radiation and others not. The methodologies employed vary from highly simplified analysis to much more detailed, computationally expensive methods (often via commercial CFD codes) with sometimes conflicting results and conclusions reported. In [1]–[3], the authors regarded the radiative heat transfer to have a great effect on the heat transfer rate in SOFCs. References [4], [5] investigated the effects of radiative heat transfer in the electrode and the electrolyte layers. Their results revealed that the electrodes can be regarded as optical transparent material, and the radiative heat transfer within the electrodes had a negligible effect on the average cell operating temperature, voltage, or temperature gradients. However, the effects of radiation heat transfer within the electrolyte depend on the thickness of electrolyte layer, i.e., the thicker the electrolyte layer, the greater the impact of radiative heat transfer. The radiative heat transfer had little influence when the thickness of the electrolyte was less than 15m. The same conclusion was

drawn by [6]. The radiative heat transfer with the participating media in SOFCs was investigated in detail by [7]. Because of the low emissivity of the gas and the small channel sizes, the gas was optically thin, and the effect of participating media on thermal radiation was minimal in the planar geometry, but it was likely to be significant in the tubular geometry. Reference [8] also investigated the radiative heat transfer with participating media in the anode and they found it had little influence on the performance of SOFCs under the ordinary operation conditions. They also indicated that the surface-to-surface thermal radiation in the flow channels had great effects on the SOFCs. Reference [9] numerically investigated the effects of surface-to-surface thermal radiation on the performance of planar SOFCs, and revealed that the temperature distribution in the cell became flat as the radiative heat exchange inside the channels was considered. The radiative heat transfer has received much more attention in recent years [10]–[13]. Based on a Monte Carlo Ray Tracing method, a numerical methodology aimed to predict the thermal radiation of materials used in the cell design with a planar geometry was developed in [10]. Reference [11] developed a relatively simple model to rapidly evaluate various configurations and operating conditions for tubular anode-supported SOFC stacks, and they concluded that the radiative heat transfer is remarkably effective at removing the heat from tube bundles of the stack. A surface-to-surface radiation model was employed in [12] to analyze the influence of different operating conditions on the temperature distribution in the anode supported tubular cell. A mathematical evaluation of view factors for radiative heat exchange in longitudinally distributed SOFC modeling was introduced by [13]. The detailed radiation model based on analytical view factors predicted more uniform distribution of the cell temperature and current density in the overall SOFC modeling. Nevertheless, most of the existing heat transfer models for the SOFCs simply ignored the effect of thermal radiation [14], even though this effect is important when the cell operating temperature is higher than 800K [2].

The present work studies the radiation effect within the solid anode, electrolyte, and cathode SOFC layers. Although it may seem likely that radiation could be important within these solid ceramic layers because of the high operating temperature. This is in fact not a reasonable hypothesis given the thickness of the electrode and electrolyte layers. The study is performed for three geometries: anode supported, cathode supported and electrolyte supported. In addition to the radiation source, only the Joule effect is considered as a heat

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source. Lattice Boltzmann method is used to solve conduction-radiation equation in SOFC components.

II. MATHEMATICAL FORMULATION

A. Problem Statement

The physical models considered here are represented in Fig. 1. In general, the electrolyte and the porous electrodes of SOFCs are semitransparent materials; that is, they can absorb, scatter, and emit thermal radiation. The energy equation is:

$$\rho c_p \frac{\partial T}{\partial t} = k \nabla^2 T - \vec{\nabla} \cdot \vec{q}_R + S_{\text{Ohm}} \quad (1)$$

where ρ is the density, c_p is the specific heat, k is the thermal conductivity, \vec{q}_R is the radiative heat flux and S_{Ohm} is the heat source by Joule effect.

B. Ohmic Source Expression

The Ohmic source is caused by Joule effect in the three components of SOFC: Cathode, Electrolyte and Anode. The heat source by Joule effect is given by the following expression [15]:

$$S_{\text{Ohm}i} = \frac{j^2}{\sigma_i} \quad (2)$$

i : anode, cathode and electrolyte where j is the current density that we suppose as constant in the entire cell. The anode, electrolyte and cathode electric conductivities are calculated according to the expressions given by:

$$\sigma_{an} = \frac{95 \times 10^6}{T} \exp\left(-\frac{1150}{T}\right) \quad (3)$$

$$\sigma_{ca} = \frac{42 \times 10^6}{T} \exp\left(-\frac{1200}{T}\right)$$

$$\sigma_{el} = 3.34 \times 10^4 \exp\left(-\frac{10300}{T}\right)$$

C. Radiative Properties

The electrodes and the electrolyte have different radiative properties. The experimental data [16] suggest that SOFC electrodes are opaque and, therefore, the optical distance $\tau_L = \beta L \gg 1$, in this case, the Rosseland approximation can be invoked. The Rosseland radiative “conductivity” defined as:

$$k_r = \frac{16n^2\sigma T^3}{3\beta} \quad (4)$$

where T is the absolute local temperature (K), σ the Stefan-Boltzmann constant ($5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^4$), n is the refractive index of the medium, and β is the spectrally averaged Rosseland-mean extinction coefficient of the medium. The radiative heat flux from Rosseland model is given by:

$$\vec{q}_R = -k_r \vec{\nabla} T \quad (5)$$

On the other hand, the electrolyte appears to be optically thin [16] [$\tau_L = \beta L \leq 1$, and can be considered an isotropic, non-diffusing gray medium [2] in the case of a 1D, plane-parallel medium, the Schuster-Schwartzschild two-flux method can be used to solve the radiative energy equation (RTE). The Schuster-Schwartzschild method is one of the oldest RTE solution techniques, and is still used to analyze systems in which radiation heat transfer is demonstrably 1D. For a gray, non-scattering medium confined between two isothermal, parallel black plates at temperatures T_{top} and T_{bottom} and separated by a distance L , the two-flux model gives the radiative heat flux as:

$$q_R = -\sigma(T_{\text{top}}^4 - T^4)e^{-2\kappa y} + \sigma(T_{\text{bot}}^4 - T^4)e^{-2\kappa y} \quad (6)$$

D. Lattice Boltzmann Simulation

For a two-dimensional geometry, in the LBM with a D2Q9 lattice, the discrete Boltzmann equation with Bhatnagar-Gross-Krook (BGK) approximation is given by [17]:

$$\frac{\partial f_i(\vec{x}, t)}{\partial t} + \vec{e}_i \cdot \nabla f_i(\vec{x}, t) = -\frac{1}{\tau} [f_i(\vec{x}, t) - f_i^{eq}(\vec{x}, t)] \quad i = 0-8 \quad (7)$$

where f_i is the particle distribution function denoting the number of particles at the lattice node \vec{x} and time t moving in direction i with velocity \vec{e}_i along the lattice $\Delta x = \vec{e}_i \Delta t$ connecting the neighbors, τ is the relaxation time, and f_i^{eq} is the equilibrium distribution function. The relaxation time τ for the D2Q9 lattice is computed from:

$$\tau = \frac{3\alpha}{|\vec{e}_i|^2} + \frac{\Delta t}{2} \quad (8)$$

where α is the thermal diffusivity. For this lattice, the 9 velocities and their corresponding weights are given by:

$$e_{1,3} = (\pm 1, 0) \frac{\Delta r}{\Delta t}, \quad e_{2,4} = (0, \pm 1) \frac{\Delta r}{\Delta t}, \quad (9)$$

$$e_{5,8} = (\pm 1, \pm 1) \frac{\Delta r}{\Delta t}, \quad e_0 = (0, 0)$$

$$w_0 = \frac{4}{9}, w_{1,4} = \frac{1}{9}, w_{5,8} = \frac{1}{36} \quad (10)$$

After discretization, (7) is written as:

$$f_i(\vec{x} + \vec{e}_i \Delta t, t + \Delta t) = f_i(\vec{x}, t) - \frac{1}{\tau} [f_i(\vec{x}, t) - f_i^{eq}(\vec{x}, t)] \quad (11)$$

The temperature is obtained after summing f_i over all direction:

$$T(\vec{x}, t) = \sum_{i=0,8} f_i(\vec{x}, t) \quad (12)$$

To process (11), an equilibrium distribution function is required, which for a conduction problem is given by:

$$f_i^{eq}(\vec{x}, t) = w_i T(\vec{x}, t) \quad (13)$$

To account for the volumetric radiation, the energy equation in the LBM formulation, (6) is modified to [16]:

$$f_i(\vec{x} + \vec{e}_i \Delta t, t + \Delta t) = f_i(\vec{x}, t) - \frac{1}{\tau} [f_i(\vec{x}, t) - f_i^{eq}(\vec{x}, t)] - \frac{\Delta t w_i}{\rho c_p} (\vec{\nabla} \cdot \vec{q}_R - S_{Ohm}) \quad (14)$$

III. VALIDATION OF THE NUMERICAL CODE

In order to check on the accuracy of the numerical technique employed for the solution of the considered problem, the present numerical code was validated with the published study of [15] is represented in Figs. 2 (a)-(c).

Figs. 2 (a)-(c) show the temperature distribution, in the absence of the radiative term source, for three geometries: (a) anode supported, (b) cathode supported and (c) electrolyte supported. It can be seen that in all cases, found results are in good agreement with those published.

IV. RESULTS AND DISCUSSION

The heat distribution is studied as a function of several parameters such as the operating temperature, cell voltages and electrolyte thickness; the effects of these parameters, in the absence and presence of the radiation, are shown in the temperature distribution and the maximum temperature.

Figs. 3 (a)-(c) show the temperature distribution in the presence of the radiation effect for three cases: (a) anode supported, (b) cathode supported and (c) electrolyte supported. For all cases, the presence of the radiative source term does

not modify the temperature distribution but reduces the maximum temperature in the SOFC.

Table I presents for the three cases studied, the maximum value of temperature in the presence and in the absence of the radiation effect, and the difference between them. The Joule effect is very important in the electrolyte due to its very low electrical conductivity. For this, the maximum values of the temperature are obtained for the geometry electrolyte supported. The radiation effect is to reduce the temperature in the SOFC. The temperature varying for the three cases studied is very low, the radiative term effect can be neglect. Since it does not influence the temperature distribution, also it does not provide a significant temperature difference.

V. CONCLUSION

Conduction–radiation problem in two-dimensional gray planar absorbing, emitting and anisotropically scattering medium has been investigated by the LBM. The Rosseland method is used to model the radiative transfer in the electrodes. The Schuster-Schwarzschild method is used to model the radiative transfer in the electrolyte. Without radiative effect, the found results are in good agreement with those published. The obtained results show that the radiative effect can be neglected.

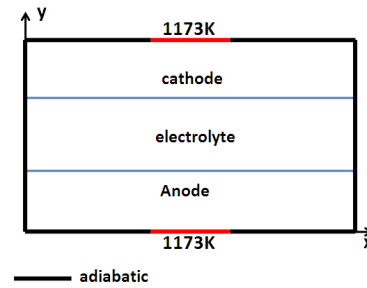
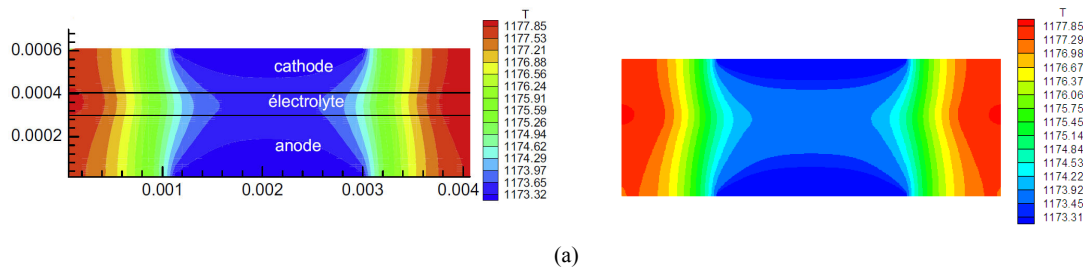


Fig. 1 The physical models

TABLE I
THE MAXIMUM VALUE OF TEMPERATURE IN THE PRESENCE AND IN THE ABSENCE OF THE RADIATION

| Thickness (μm) Anode/electrolyte/cathode | Tmax (K) | | ΔTmax (K) |
|--|--------------------------|-----------------------|-----------|
| | without radiation effect | with radiation effect | |
| anode supported (300/100/200) | 1177.85 | 1176.99 | 0.86 |
| cathode supported (200/100/300) | 1177.86 | 1177.32 | 0.54 |
| electrolyte supported (100/200 /100) | 1184.65 | 1183.86 | 0.79 |



(a)

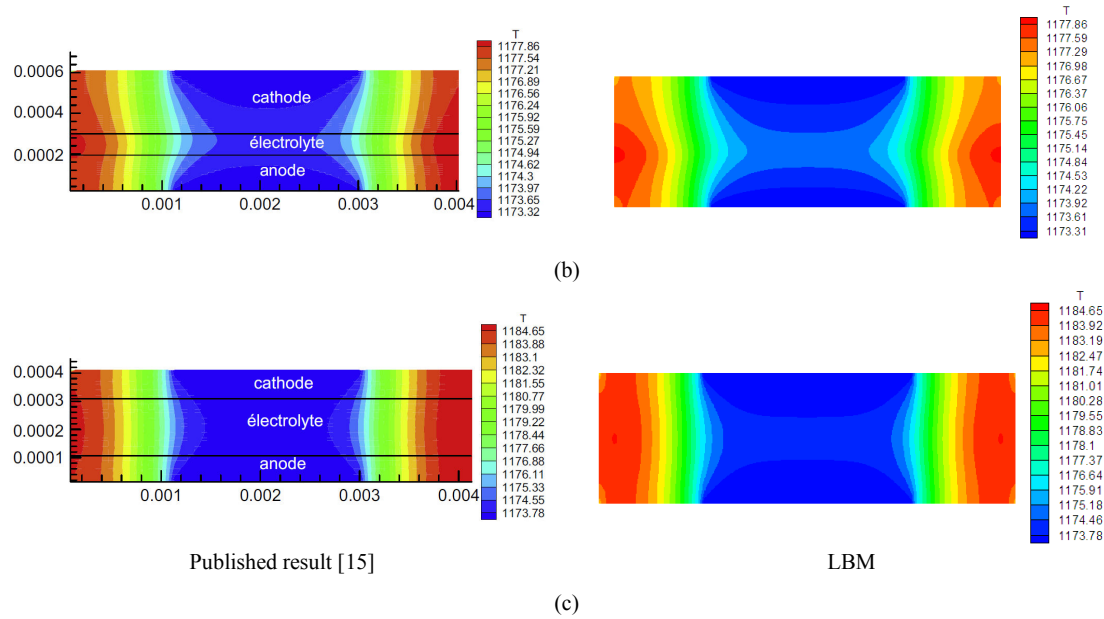


Fig. 2 The temperature distribution, in the absence of the radiative term source, for three geometries: (a) anode supported, (b) cathode supported and (c) electrolyte supported

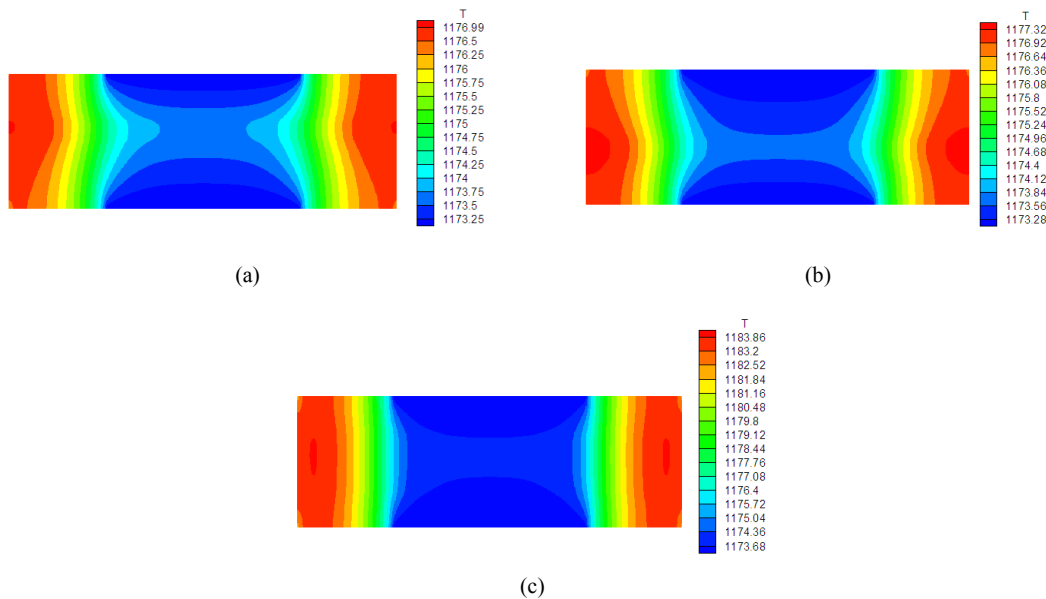


Fig. 3 The temperature distribution in the presence of the radiation effect for three cases: (a) anode supported, (b) cathode supported and (c) electrolyte supported

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