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RADIATION HEAT TRANSFER IN SOFC ELECTROLYTES

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ABSTRACT

Due to their high operating temperature, there has been speculation that thermal radiation may play an important role in the overall heat transfer within the electrode and electrolyte layers of solid oxide fuel cells (SOFCs). This paper presents a detailed characterization of the thermophysical and radiative properties of the composite materials, which are then used to define a simple 2-D model incorporating the heat transfer characteristics of the electrode and electrolyte layers of a typical planar SOFC. Subsequently, the importance of thermal radiation is assessed by comparing the temperature field obtained using a conduction model with fields obtained using coupled conduction/radiation models. Contrary to some published literature, these results show that radiation heat transfer has a negligible effect on the temperature field within these components, and does not need to be accommodated in comprehensive thermal models of planar SOFCs.

INTRODUCTION

Due to their high thermal efficiency, high quality of heat output, and fuel flexibility, solid oxide fuel cells (SOFCs) may soon replace more traditional devices currently used to generate electricity in many applications. Thermal modeling is integral part to the development of this emerging technology, since the temperature field is needed to calculate the electrochemical reaction rates, electrode overpotentials, and ohmic resistances that govern fuel cell performance. Furthermore, an accurate thermal analysis is required to assess the mechanical soundness of the device, as typical SOFC operating temperatures approach the service temperatures of the component materials.

Because of their high operating temperature, there has been some speculation that thermal radiation may be an important component of heat transfer within SOFCs. Several studies have focused on the effect of radiation heat transfer in the fuel and air channels within planar and tubular SOFCs [1-3]. These studies have all found that this phenomenon plays a minor effect on the overall temperature distribution within the fuel cell relative to other modes of heat transfer.

The present work instead focuses on radiation heat transfer within the solid anode, electrolyte, and cathode SOFC layers. Although it may seem unlikely that radiation could be important within these solid ceramic and cermet layers, this is not an unreasonable hypothesis given the high temperatures involved and the thickness of the electrode and electrolyte layers. Indeed, thermal radiation is known to be an important mode of heat transfer through ceramic thermal barrier coatings used in high temperature applications, which have approximately the same thickness as the ceramic electrolyte layer in the present application [4].

Nevertheless, detailed study of radiation transfer through the SOFC electrode and electrolyte layers has been quite limited to date. Murthy and Fedorov [5] analyzed radiation heat transfer between the air and fuel channels in a two-dimensional electrolyte-supported counter-flow SOFC. Radiation heat transfer through the optically-thin electrolyte was modeled using the Schuster-Schwarzschild two-flux method, while radiation within the optically-thick electrodes was simulated by the diffusion approximation. Both radiation models were incorporated into a coupled CFD/electrochemistry simulation of the temperature field. This study found that ignoring radiation heat transfer caused errors of more than 10% (approximately 100 K) in the temperature field.

More recently, Damm and Fedorov [6] studied radiation within a two-dimensional anode-supported counter-flow SOFC. The Schuster-Schwarzschild method was again used to model radiation heat transfer through the electrolyte, but in this treatment the electrodes were both assumed to be opaque and consequently excluded from the radiation analysis. In contrast to the previous paper, this study found that neglecting radiation in the thermal model accounts for only a few degrees error in the SOFC temperature field. The authors attribute the difference between their results and those of Murthy and Fedorov [5] to the different SOFC geometries studied.

In this paper we seek to determine if radiation heat transfer is an important phenomenon in the electrode and electrolyte layers of typical planar SOFCs. This is done by first performing a detailed analysis of the thermophysical and

optical properties of the component materials. Next, a simplified 2-D thermal model of an anode-supported SOFC is developed, based on the important heat transfer and heat generation mechanisms in the fuel cell. Finally, the importance of thermal radiation relative to other modes of heat transfer is assessed by comparing the temperature field obtained using a conduction model to those obtained using coupled conduction/Monte Carlo and conduction/Schuster-Schwarzschild models. These results show that thermal radiation has a minimal effect on the temperature field within the electrode and electrolyte layers, suggesting that this phenomenon can be excluded from detailed SOFC thermal models.

NOMENCLATURE

c_p	Specific heat, J/kgK
$E_b(\lambda)$	Blackbody emissive power, W/m^2
F	Faraday's constant, $96.487 \times 10^3 \text{ V/mol electrons}$
h	Convection coefficient, W/m^2K
i''	Current density, A/m^2
k	Thermal conductivity, W/mK
$\dot{m}'$	Mass flow rate per unit channel thickness, $kg/s \cdot m$
M	Molar mass, kg/mol
$\dot{q}$	Volumetric heat source, W/m^3
q''	Heat flux, W/m^2
S	Molar entropy, $J/molK$
T	Temperature, K
u	Utilization rate
y	Mole fraction
α	Absorption coefficient, m^{-1}
δ	Reaction zone thickness, μm
ϵ	Surface emissivity
λ	Wavelength, μm
η	Electrode overpotential, V
Ω	Scattering albedo, $\sigma_s/(\alpha + \sigma_s)$
ρ	Density, kg/m^3
ρ_e	Electrolyte ohmic resistivity, $\Omega \cdot m$
σ_s	Scattering coefficient, m^{-1}

Subscripts and superscripts

a	Anode
c	Cathode
e	Electrolyte
irr	Irreversible
rev	Reversible

SOLID OXIDE FUEL CELLS

Solid oxide fuel cells are solid-state devices that convert the chemical potential in a fuel and oxygen directly into electricity, by taking advantage of the capacity of zirconia to conduct oxygen ions. A cell consists of three layers, as shown in Fig. 1: an anode layer composed of porous cermet (most often a combination of Ni and yttria-stabilized zirconia, YSZ), a solid electrolyte layer composed of YSZ, and a

cathode made up of porous strontium-doped lanthanum manganate ($LaMnO_3$), a perovskite. These layers are arranged in planar or tubular configurations to create a single cell (this paper focuses on the planar arrangement.) One of the three layers provides structural support and is consequently thicker than the other two; the majority of SOFCs are anode- or cathode-supported, since a thin electrolyte layer facilitates ion transfer between the electrodes. Air channels provide oxygen to the cathode, while fuel channels provide hydrogen and remove water vapor from the anode. Individual SOFC cells are encased in a stainless-steel or ceramic interconnect and then connected electrically to form a SOFC stack.

Electricity is generated by the electrochemical reactions at the electrode-electrolyte interfaces, as shown in Fig. 2. (The porosity of the electrodes enables the reactants and products to migrate between the electrode surface and the electrode-electrolyte interface.) At the cathode-electrolyte interface, oxygen is combined with electrons supplied by the interconnect to yield oxygen ions,

The oxygen ions travel across the electrode to the anode-electrolyte interface. Here, they combine with the hydrogen fuel to yield water and electrons,

which are removed by the fuel channel and interconnect respectively. Thus, the overall chemical reaction is

If CH_4 is used as a fuel, additional reforming reactions occur within the fuel channel and at the anode surface; in this work, the only fuel considered is H_2 . A thorough description of the structure and electrochemistry within a solid oxide fuel cell is provided by Beale [7].

Fig. 1: Solid oxide fuel cell.

Fig. 2: Schematic of electrochemical reactions.

HEAT TRANSFER IN SOLID OXIDE FUEL CELLS

Heat is generated by reversible and irreversible mechanisms inside the electrode and electrolyte layers, and is removed predominantly by convection through the air and fuel channels.

In the majority of SOFC simulations, the overall heat generation rate is first calculated by applying the 1st law of thermodynamics to Eq. (3), subsequently modeled as either uniform volumetric generation through the electrolyte [2], or a uniform planar heat source at the cathode/electrolyte interface [8]. Although this treatment is sufficient to provide a rough approximation of the large-scale temperature variation within a SOFC, a more accurate estimate of the temperature field is required to assess the importance of radiation heat transfer across the electrode and electrolyte layers. Accordingly, in this application each heat generation mechanism is modeled at the location it occurs within the SOFC as described by Khaleel and Selman [9].

Most of the heat generated within the SOFC is due to reversible and irreversible processes occurring at the electrode/electrolyte interfaces within thin reaction zones called *triple-phase boundaries*; since these processes are surface phenomena, the corresponding heat generation terms are appropriately modeled as planar heat sources. Reversible heat generation is due to entropy transfer by the electrochemical reactions at the cathode and anode,

$$q_{rev,c}'' = T(2S_{O_2} - S_{O_2} - 4S_{e^-}) \frac{i''}{4F} \quad (4)$$

and

$$q_{rev,a}'' = T(2S_{H_2O} - 2S_{H_2} - 2S_{O_2} + 4S_{e^-}) \frac{i''}{4F}, \quad (5)$$

where i'' is the local current density, F is Faraday's constant, and the S_x terms denote the molar entropies of the products and reactants at the operating temperature and pressure. Under standard operating conditions entropy is consumed at the cathode and produced at the anode, so Eqs. (1) and (2) are exothermic and endothermic, respectively [10]. Equations (4) and (5) cannot be solved directly since the molar entropies of half-reaction stages are generally unknown. Instead, an experimentally-determined value for the entropy change at the cathode is taken from Kanamura et al. [10] and the entropy change at the anode is then inferred from the relation $\Delta S_a =$

$\Delta S_{tot} - \Delta S_c$, where ΔS_{tot} is the overall entropy change associated with Eq. (3). (The overall entropy change is calculated assuming all products and reactants are at 1000 K, and partial pressures of O_2 , H_2 , and H_2O equal to 0.21 atm, 0.75 atm, and 0.25 atm, respectively.)

Irreversible heat generation at the electrode/electrolyte interfaces is caused by the irreversibilities associated with ion transfer across these interfaces that are often referred to as the *cathodic* and *anodic overpotentials*, η_c and η_a , respectively. These quantities are most often expressed in units of volts, and accordingly the corresponding heat generation rates associated with these irreversibilities are $q_{irr,c}'' = i''\eta_c$ and $q_{irr,a}'' = i''\eta_a$. Although the electrode overpotentials can be estimated from phenomenological equations [7], the present simulation assumes typical values for η_c and η_a based on experimental studies [11, 12].

A third source of heat generation is due to volumetric Ohmic heating in the electrolyte due to the conduction of oxygen ions, $\dot{q}_{ohm} = \rho_e(T)i''^2$, where $\rho_e(T)$ is the temperature-dependent ionic resistivity of the electrolyte. (A temperature-dependent correlation of $\rho_e(T)$ is provided in [13]) Although this effect is neglected when simulating most other types of fuel cells, Ohmic heating must be included in SOFC models due to the large ionic resistance of YSZ compared to that of electrolyte materials used in other fuel cells.

Heat generated within the electrode and electrolyte layers of the SOFC is removed predominantly by the fuel and air channels. The inlet temperatures of the air and fuel channels determine the lower operating temperature of the fuel cell; in SOFCs, the air and fuel are preheated to approximately 950 K to facilitate electrochemical and reforming reactions that occur within the fuel cell. The upper operating temperature depends on the fuel and air mass flow rates and the rate of energy generation within the fuel cell.

PROPERTY CHARACTERIZATION

As previously mentioned, there is considerable motivation for developing accurate SOFC thermal models, and to that end high-temperature experimental studies have been performed to characterize the thermal conductivities of different SOFC materials [14-16], which are summarized in Table 1.

Far less emphasis has been placed on the experimental determination of radiative properties, since most previous SOFC thermal models have neglected thermal radiation within the composite layers. The electrolyte material is the best characterized of the layers; experimental determination of the radiative properties of polycrystalline YSZ has been largely motivated by its use as a thermal barrier coating. Makino et al. [17] inferred the spectral absorption and scattering properties of 6% porous YSZ by applying a four-flux model to spectral reflection and transmission data obtained from a thin

ceramic laminate; these distributions are shown in Fig. 3, along with the shape of Planck's distribution at 1000 K. Scattering dominates the extinction coefficient at short wavelengths ($\lambda \leq 5 \mu\text{m}$) and is caused by refraction as radiation traverses the solid-pore interface, since the refractive indices of the ceramic and the pore void are different; a rigorous description of this phenomenon is provided by Van de Hulst [18]. (Scattering also occurs at grain boundaries, but to a lesser extent.) Due to the high density of scattering sites within ceramics, radiation is multiply scattered, so the scattering can be assumed to be isotropic [17]. Infrared absorption in YSZ is due to lattice vibrations at long wavelengths ($\lambda > 3 \mu\text{m}$), and can be accurately modeled using Lorentz theory [19]. The Planck mean absorption and scattering coefficients at 1000 K are $\alpha_p = 260 \text{ m}^{-1}$ and $\sigma_{s,p} = 1 \times 10^4 \text{ m}^{-1}$, respectively; these values are used in the heat transfer model presented later in the paper.

Determining the radiative properties of the electrodes is more problematic. A recent study was unable to find the absorption and scattering coefficients of these materials through infrared spectrometry due to their high opacities [6]. Furthermore, numerical modeling of scattering in microporous materials is generally not possible since it is strongly dependent; scattering in the cermet is also complicated by reflection at metal/ceramic interfaces. Despite these difficulties, however, the importance of thermal radiation within the anode and cathode can be assessed by examining the magnitude of the extinction coefficients, which are greater than or equal to the magnitude of the absorption coefficients. These, in turn, are estimated by applying appropriate analytical models to the electromagnetic properties of the bulk materials.

The absorption coefficient of LaMnO_3 is estimated by performing a Kramers-Kronig analysis [20] on the spectral, normal reflectance data of a single LaMnO_3 crystal presented in Okimoto et al. [21]. This analysis is based on the relationship

$$\delta(\eta) = \frac{\eta}{\pi} PV \left[\int_0^\infty \frac{\ln \rho_n(\eta')}{\eta'^2 - \eta^2} d\eta' \right], \quad (6)$$

where η is the wavenumber and $\delta(\eta)$ is the phase angle of the complex refraction coefficient, defined implicitly as

$$\sqrt{\rho_n(\eta)} [\cos \delta(\eta) + i \sin \delta(\eta)] = \frac{(n-1)^2 + k^2}{(n+1)^2 + k^2}. \quad (7)$$

Once Eq. (7) has been solved for n and k , the absorption coefficient is found from $\alpha(\lambda) = 4\pi k/n\lambda$, which is plotted in Fig. 4.

The absorption coefficient of the Ni-YSZ anode material is estimated using an effective medium theory [22]. In this approach, the composite is modeled as a homogeneous effective medium having optical properties calculated from those of the constituent materials. The functional relationship used to calculate the optical properties of the effective medium is derived by applying Mie scattering theory to

analyze a system consisting of a *random unit cell* embedded within the effective medium. The random unit cell is made up of the constituent materials in a simplified (usually spherical) arrangement that represents the composite microstructure, and the optical properties of the effective medium must then make this random unit cell "invisible" when viewed from outside the system. The accuracy and applicability of an effective medium theory as a model for a particular material depends on the microstructure and optical properties of the constituent materials, and consequently the random unit cell used in the derivation of the effective medium theory. Bruggeman's theory is the most suitable for modeling the Ni-YSZ cermet, since its random unit cell assumes that the composite materials enter on an equal footing to form a space-filling random mixture, which describes the microstructure of an anode made by sintering a roughly equal mixture of the constituent materials in powdered form. The complex dielectric function of Bruggeman's effective medium, ϵ_{Br} , is found by solving

$$f_A \frac{\epsilon_A - \epsilon_{Br}}{\epsilon_A + 2\epsilon_{Br}} + (1 - f_A) \frac{\epsilon_B - \epsilon_{Br}}{\epsilon_B + 2\epsilon_{Br}} = 0, \quad (8)$$

where ϵ_A and ϵ_B are the complex dielectric functions of ZrO_2 [19] and Ni [23], respectively, and f_A is the filling factor of the ZrO_2 , which is assumed to be 50%. The absorption coefficient of the effective medium is then calculated from ϵ_{Br} , and is plotted in Fig. 4.

Figure 4 shows that the magnitude of the absorption coefficient is such that the mean penetration distance of radiation is no greater than $2 \mu\text{m}$ and 2 nm for the cathode and anode materials, respectively. The actual mean penetration distances are less than these estimates since scattering has been neglected in the extinction coefficient and no doubt plays an important role given the microstructures of these materials. This justifies the assumption of negligible radiation within the anode and cathode layers, which is made in the majority of previous SOFC heat transfer studies [1-3, 6].

It should be noted that there is some question of how accurately the radiative properties of the bulk electrode and electrolyte materials describe those of the corresponding layers within an SOFC. The scattering behavior of the YSZ electrolyte is particularly questionable, given that the pore spacing is approximately the same order of magnitude as the electrolyte layer thickness.

DEVELOPMENT OF A 2-D HEAT TRANSFER MODEL

Computational Domain: Due to the complex nature of SOFCs (which involve multicomponent flow, multimode heat transfer, and electrochemistry) and the size of the computational domain, detailed CFD simulations are notoriously expensive and can incorporate only the simplest radiation models while still remaining computationally tractable. Because of this, our analysis is instead based on a 2-D conduction/radiation problem with heat transfer characteristics similar to a SOFC, but is simple enough to accommodate more detailed radiation models that can

accurately assess the importance of thermal radiation in the electrode/electrolyte layers.

Table 1: Thermal conductivity of SOFC layers.

Material	Porosity	k [W/mK]
YSZ (electrolyte)	6%	2.3 [14]
LaMnO ₃ (cathode)	40%	0.8 [15]
50% Ni-YSZ (anode)	40%	3.7 [16]

Fig. 3: Radiative properties of YSZ electrolyte [17].

Fig. 4: Absorption coefficients for bulk anode and cathode materials

This model is based on a 0.1 m long counter-flow anode-supported SOFC geometry shown in Fig. 5 (a). The fuel and air channels are 1 mm wide, and the anode, electrolyte, and cathode layer thicknesses are 1000 μm , 15 μm , and 50 μm respectively. The thermal conductivities of the electrodes and electrolyte are given in Table 1, and the composition and properties of the fuel and air are summarized in Table 2. The radiation subdomain, shown in Fig. 5 (b) includes only the

electrolyte layer, due to the aforementioned opacity of the electrodes.

Fig. 5: Development of 2-D heat transfer model (a) conduction domain, and (b) radiation domain.

Table 2: Composition and properties of air and fuel.

Property	Air	Fuel
ρ , kg/m ³	0.399	0.255
c_p , kJ/kgK	1.129	1.673
k , W/mK	0.067	0.080
y_{O_2}	0.225	0
y_{H_2}	0.775	0.85
y_{N_2}	0	0.10
$y_{\text{H}_2\text{O}}$	0	0.05

Boundary Conditions: Four boundary conditions must be prescribed over the edges of the computational domain in order to solve for the temperature field.

A convection boundary condition is prescribed over the upper and lower surfaces of the anode and cathode layers, respectively. The air and fuel inlet temperatures are set equal to 950 K, and a uniform current density of 4000 A/m² is assumed, which are typical values for this type of fuel cell. The air flow rate is calculated by modifying Eq. (1),

$$\dot{m}'_{\text{air}} = \frac{i^n}{4F u_{\text{O}_2}} \times L \times \frac{n_{\text{air}}}{n_{\text{O}_2}} \times M_{\text{air}}, \quad (9)$$

where L is the length of the air channel, u_{O_2} is the oxygen utilization rate, M_{air} is the molar mass of air, and $n_{\text{air}}/n_{\text{O}_2}$ is the number of moles of air containing one mole of O₂. The mass flow rate of fuel is calculated by modifying Eq. (2) in a similar way,

$$\dot{m}'_{fuel} = \frac{i''}{2F u_{H_2}} \times L \times \frac{n_{fuel}}{n_{H_2}} \times M_{fuel}, \quad (10)$$

where u_{H_2} is the hydrogen utilization rate, M_{fuel} is the molar mass of fuel, and n_{fuel}/n_{H_2} is the number of moles of fuel containing one mole of H_2 . Substituting the properties in Table 2 into Eqs. (9) and (10) and assuming oxygen and hydrogen utilization rates of 20% and 80% respectively gives $\dot{m}'_{air} = 6.649 \times 10^{-4} \text{ kg/ms}$, and $\dot{m}'_{fuel} = 6.452 \times 10^{-4} \text{ kg/ms}$.

The convection coefficients in the air and fuel channels are found using the Nusselt number for laminar flow through a slot in which one surface is adiabatic and the other surface has a constant heat flux boundary condition, $Nu_{Dh} = 5.385$ [24], where the hydraulic diameter, $D_{h,i}$, is equal to the channel half-width. Carrying out the calculations gives $h_{air} = 181 \text{ W/m}^2\text{K}$ and $h_{fuel} = 215 \text{ W/m}^2\text{K}$.

Heat generation terms in the anode, cathode, and electrolyte are calculated as described in the previous section assuming a uniform current density of 4000 A/m^2 , anodic and cathodic overpotentials of 1 V [11] and 1.5 V [12] respectively, and an electrolyte ionic resistivity $\rho_e(1000 \text{ K}) = 0.8901 \Omega \cdot \text{m}$ [13]. The corresponding heat generation terms are summarized in Table 3. Since it is impractical to prescribe a planar heat source between interior control volumes, heat generation at the electrode/electrolyte interfaces is assumed to occur uniformly within a reaction zone on the electrode side having a thickness of $1 \mu\text{m}$ as indicated in Fig. 5 (a).

The boundary conditions of the radiation sub-domain are specified with the temperature obtained from the most recent conduction solution. The emissivities of the upper and lower boundaries, representing the anode/electrolyte and cathode/electrolyte interfaces respectively, are assumed to be 0.9, which is reasonable for a porous ceramic surface. The emissivities of the lateral surfaces are set equal to 0.5, which is typical for a rough, lightly-oxidized metal surface. The porous medium is treated as grey and the absorption and scattering coefficients are set equal to the Planck mean values evaluated at 1000 K ; this is a reasonable assumption, given the small degree of temperature variation over the radiation domain.

Table 3: Heat generation terms in SOFC layers.

Layer	Source Term
Anode	$q''_{irr,a} = 0.6 \text{ kW/m}^2$
	$q''_{rev,a} = -0.6 \text{ kW/m}^2$
Cathode	$q''_{irr,c} = 0.4 \text{ kW/m}^2$
	$q''_{rev,c} = 1.7 \text{ kW/m}^2$
Electrolyte	$\dot{q}_{ohm} = 14.7 \times 10^3 \text{ kW/m}^3$

Solution Technique: The solution procedure is initialized by solving the temperature field over the conduction domain using a second-order finite volume method coupled with a

first-order upwind scheme in the fuel and air channels. This temperature field is projected onto the radiation domain and boundaries, which in turn is solved for the radiative source term within the electrolyte and radiative fluxes crossing the electrolyte boundaries. These terms are added to the energy equations and boundary conditions on the conduction domain, which is again solved for the temperature field. This process continues until convergence is obtained.

Two different radiation solvers are employed to solve for the radiation source term in the electrolyte: the Schuster-Schwarzschild two-flux method [25] and a pathlength-based Monte Carlo method [26]. The Schuster-Schwarzschild method assumes 1-D radiation heat transfer, specifically that the intensity at any point within the medium is isotropic over a hemisphere centered in the direction of radiation heat transfer and is also isotropic over the complementary hemisphere. These assumptions transform the radiative transfer equation (RTE) into a coupled system of two first-order ordinary differential equations that can be easily solved over the problem domain using traditional numerical methods. The Schuster-Schwarzschild method is one of the oldest RTE solution techniques, and is still used analyze systems in which radiation heat transfer is demonstrably 1-D (e.g. thermal barrier coatings) and where other, more complex heat transfer modes dominate the problem, necessitating computational economy. Both Damm and Fedorov [5] and Murthy and Fedorov [4] used this method in their SOFC analyses by assuming 1-D radiation heat transfer between the electrodes.

The Monte Carlo method is more accurate than the Schuster-Schwarzschild method, but it is also more expensive. The analysis starts by specifying the energy of a single photon bundle. A large number of photon bundles are then emitted in random directions from random locations over each volume and surface element, according to predefined probability density functions; the number of emitted bundles is proportional to the emissive energy of the element. Every bundle is ray-traced through random scattering and reflection events. Each time a bundle passes through a volume element or is reflected off a wall element, energy is removed from the bundle and added to the corresponding volume or wall element. Ray-tracing continues until the bundle energy falls below a predefined termination criterion, which is set equal to 0.1% of the initial photon energy in the present analysis. Once all bundles have been emitted and absorbed, the radiative source terms and heat fluxes are computed by subtracting the energy emitted by the volume and surface elements (the number of emitted bundles times the energy per bundle) from the energy absorbed throughout the process. Although it is one of the most accurate schemes for solving radiation heat transfer problems, the Monte Carlo method is too expensive to be incorporated into a full SOFC simulation, and is only used here to treat the simplified problem shown in Fig. 5.

RESULTS AND DISCUSSION

Model Validation: The radiation/conduction solvers are first validated by using them to solve the 1-D benchmark problem of Crosbie and Viscanta [27], who provide the conduction and radiation heat flux between two temperature-specified parallel grey walls that bound an absorbing, emitting, and scattering medium. The 1-D problem is approximated by a 2-D problem having an aspect ratio of 20:1 shown in Fig. 6, and the results are taken from the x -midplane. Table 4 shows that the total (non-dimensional) heat flux across the two plates obtained using the Schuster-Schwarzchild and Monte Carlo methods for different scattering albedo values are in good agreement with the benchmark solutions.

$$N = k(\alpha + \sigma_s)/4\sigma T_1^3 = 0.1, H(\alpha + \sigma_s) = 1, T_1/T_2 = 2, L/H = 20$$

Fig. 6: Benchmark problem.

Table 4: Model and benchmark results.

$\sigma_s/(\sigma_s + \alpha)$	$q_{12}/\sigma T_1^4$		
	Schuster-Schwarzchild	Monte Carlo	Benchmark Solution [27]
0	0.546	0.558	0.571
0.5	0.502	0.518	0.513
1	0.434	0.447	0.449

Influence of Radiation on Temperature Distribution: Next, the importance of radiation heat transfer is assessed by comparing the temperature fields within the electrolyte layer found using the coupled conduction/radiation solvers to the one obtained using the conduction solver alone. The temperature distributions along the horizontal and vertical electrolyte midplanes obtained by the three methods are shown in Figs. 7 and 8. In Fig. 7, the temperature distributions along the y -midplane obtained using the coupled Schuster-Schwarzchild/conduction and Monte-Carlo/conduction solvers are indistinguishable from the conduction solution, which varies from 988 K at $x = 0$ mm to 1102 K at $x = 100$ mm, with a maximum temperature of 1346 K at 71 mm. Figure 8 shows that upon closer inspection, the temperature distributions obtained along the x -midplane using the conduction and Schuster-Schwarzchild/conduction solvers are nearly identical, while the one obtained using the Monte-Carlo/conduction solver is lower by approximately 1.5 K. This inconsistency is likely due to the photon bundle termination criterion in the Monte Carlo simulation, which makes the method slightly non-conservative.

This conclusion was also reached by Damm and Fedorov [6], but not by Murthy and Fedorov [5]; the former found that

neglecting radiation results in errors of less than 1 K in the temperature field of an anode-supported SOFC, while the latter claims that this assumption leads to errors larger than 100 K within an electrolyte-supported SOFC. Damm and Fedorov [6] account for this difference by noting that the temperature variation between the electrodes in an electrolyte-supported SOFC is much larger than that of an electrode-supported SOFC due to the comparatively high conduction resistance across the electrolyte in the former type of fuel cell. As shown in Table 5, Murthy and Fedorov [5] also assumed a smaller electrolyte extinction coefficient compared to values used by Damm and Fedorov [6] and the present work, which are more in line with extinction coefficients cited in other experimental and theoretical studies. This, in fact, is more likely to be the reason why the conclusions made by these papers are different.

Table 5: Electrolyte radiative properties.

	$(\sigma_s + \alpha) [m^{-1}]$	$\Omega = \sigma_s/(\sigma_s + \alpha)$
Murthy and Fedorov [5]	500	0
Damm and Fedorov [6]	1.02×10^4	0
Present Study	1.03×10^4	0.97

*Planck mean value at 1000 K from three-band model

CONCLUSIONS AND FUTURE WORK

This paper evaluated the importance of thermal radiation heat transfer in the electrode and electrolyte layers within planar SOFCs. This was done by first characterizing the thermophysical and radiation properties of the component materials and then developing a 2-D model of an anode-supported SOFC based on the sources of heat generation within the electrode and electrolyte layers. The importance and nature of thermal radiation was then determined by comparing the temperature distributions obtained using coupled Schuster-Schwarzchild/conduction and Monte-Carlo/conduction solvers to the one calculated assuming conduction as the only mode of heat transfer.

The results show that thermal radiation has a negligible effect on the temperature field in the electrode and electrolyte layers. Due to the minor effect thermal radiation has on the temperature field (which is likely smaller in magnitude than errors induced by other modeling assumptions) thermal radiation can safely be excluded from a detailed CFD analysis of a planar anode-supported SOFC.

Care should be taken in extending this result to other SOFC configurations, however. In particular, radiation may play a more important role in electrolyte- and cathode-supported planar SOFCs, since both of these configurations tend to have larger temperature gradients across the electrolyte compared to anode-supported SOFCs. It is also unclear whether it is appropriate to use the bulk radiative properties of the electrolyte material to model thermal radiation in the

SOFC, given the small length scales involved in this application. These questions will be addressed in future work.

Fig. 7: Temperature distribution along y-midplane.

Fig. 8: Temperature distribution along x-midplane.

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