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Radiation Heat Transfer Quantification in Solid Oxide Fuel Cell : Effect of Geometric Parameters

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Abstract

The study of the heat transfer in a SOFC based on mathematical modeling has attracted significant interest in recent years. Detailed CFD based models predict the current density, the species and the temperature distribution as well as the mass transfer within a SOFC. The inclusion of the heat radiation transfer in the analysis of the heat transfer entails a number of challenges which are not considered in the case of an analysis based only on the heat convection and the heat conduction.

In the present work, the heat radiation transfer effect on the temperature distribution in a PEN-SOFC is studied. The energy dissipation due to the Joule effect is the dominant source responsible for the heat release in the studied SOFC configuration. A two-dimensional numerical model based on the finite volume method is developed. The approximation methods are used in order to examine the heat flux within each compartment of the PEN-SOFC. The studied parameters are: the gas temperature, the current density and the SOFC dimensions.

Keywords: PEN – SOFC; temperature;SOFC configuration, radiation.

1. Radiation heat transfer in SOFC fuel cell

The study of the heat transfer in a SOFC based on mathematical modeling has attracted significant interest in recent years. Detailed CFD based models predict the current density, the species and the temperature distribution as well as the mass transfer within a SOFC [1-2]. The inclusion of the heat radiation transfer in the analysis of the heat transfer entails a number of challenges which are not considered in the case of an analysis based only on the heat convection and the heat conduction. The first is the inherent complexity of the governing equations which are integro-differential and, in general, depend on as many as seven independent variables (time, three position variables, two angular variables describing direction of propagation of radiation rays, and the wavelength). Further, the governing equations are non-linear, as the emissive power features a fourth-power dependence on temperature. Besides the difficulty associated with solving these equations, the accuracy of any analysis is always limited by the extent to which radiative properties are known. Unlike the thermophysical properties relevant to conduction or convection heat transfer, which are well behaved, rather well characterized, and usually weakly dependent on temperature, radiation properties are often highly (even erratically) dependent on wavelength of radiation and surface preparation, and a strong function of the temperature.

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Furthermore, in many cases limited experimental data exist for radiative properties. In certain cases making use of carefully justified simplifying assumptions make these difficulties manageable and accurate engineering calculations could be obtained. Even a simplified analysis can be time costly. Moreover, when the heat radiation transfer terms are concluded in the mathematical model formulation the computational time requirements are increased compared to the standard conductive-convective heat transfer calculations alone [5-6]. This fact motivates us not only to discuss the existing modeling methodologies and simplifying assumptions for heat treating radiation transfer, but also to specify the conditions under which certain effects could be neglected. In a previous work a framework for modeling radiation within the optically thick porous electrodes, and optically thin yttria-stabilized zirconia (YSZ) electrolyte, was developed [5]. It was shown that the radiation effects are significant for thicker, semitransparent electrolytes, reducing the overall operating temperature (by 150 K) and decreasing thermal gradients in the monolith type cell. Also, it was shown that the Schuster Schwarzchild's two-flux approximation gives accurate results at a fraction of the computational cost of the discrete ordinates (DO) method. In that work, the model was developed assuming few properties because the relevant radiation properties was limited. Here, experimental measurement of optical properties of the SOFC materials are reported. Since the optical properties exhibit significant spectral variation, the model is formulated on a spectral basis, still in the optically thin limit of the two-flux approximation, which is used to solve the radiation tranksfer equation (RTE) in the YSZ electrolyte layer. The divergence of the total radiative heat flux is then incorporated into the overall energy conservation equation as a heat sink term through which the user can define the function utility in the FLUENT CFD model of the SOFC.

2. Radiation properties

The electrolyte and the porous electrodes of SOFCs are semitransparent materials; thus they can absorb, scatter, and emit thermal radiation. For a linear medium, the spectral absorption coefficient, κ, refractive index, n, spectral scattering coefficient σ and the scattering phase function, Φ, provide a complete set of phenomenological properties required to model the propagation of radiative energy in the medium. In addition, emissivityε, and reflectivity, ρ, of the bounding interfaces must be provided in order to specify the boundary conditions.

These radiation properties vary typically with wavelength, and we used Planck's law to find the relevant spectral range for measurements. For typical operating temperatures of 900-1100 K and refractive index of the electrolyte, $n \approx 1.8$, it can be shown that over 90% of the emissive power is contained within the near to mid infrared spectral region, $0.9 < \lambda < 7.8$ μm.

The total thermal conduction in a homogeneous solid compound can be though as the sum of contributions from phonons, λ_P , (quantum mechanical description of vibrational atomic motion in which a lattice uniformly oscillates at the same frequency) and photons, λ_{Rad} (radiation). Eq.1

$$\lambda = \lambda_P + \lambda_{Rad} \tag{1}$$

The photon thermal conductivity of a pure solid in the absence of any extrinsic scattering by extended defects or points defects is calculated via Eq.2

$$\lambda_P = \frac{\psi}{T} \tag{2}$$

ψ is a constant and is given by : Eq.3

$$\psi = \frac{3}{2}\gamma^2\left[\frac{\mu\nu^2}{\omega_D N^{-2/3}}\right] \tag{3}$$

For the zirconia the value of ψ has been estimated to vary between 1700 and 2800 W.m^{-1}. When yttria is added, the photons can be scattered by the oxygen vacancies which are created. Furthermore for higher temperatures the photon conductivity can be reduced by the scattering of photons due to the jumping of oxygen vacancies between neighboring sites in lattice. At least the photon conductivity considering the three scattering mechanisms reported beforehand is expressed with a more complex formula than Eq.2. Heat transfer by radiation obeys to mechanisms which are active at high temperatures. For optically thick

system, the radiation conductivity λ_{Rad} is given by the Rosseland expression via Eq.4

$$\lambda_{Rad} = \frac{16n^2\sigma T_R{}^3}{3(\Gamma + K)} \tag{4}$$

Where

- n is the refractive index of the medium,
- σ is the Stefan-Boltzmann constant (5.67 108 W.m^{-2}. K^4),
- K is the total absorption coefficient,
- Γ is the total scattering coefficient, and T_R is the radiative temperature
- T_R is the radiation temperature calculated from the boundary temperature T_1 and T_2 as: Eq.5

$$T_R^3 = (1/4)(T_1^2 + T_2^2)(T_1 + T_2) \tag{5}$$

The sum of Γ and K gives the extinction coefficient which is the inverse photon mean free path. However, this approximation should be used carefully especially near the boundaries where even an optically very thick medium is locally optically thin. K is relevant to the chemical composition of the sample and Γ depends mainly on its texture. The term texture stands for the spatial repartition of the heterogeneities (grains, pores) within the host matrix and their respective characteristic size distributions. Furthermore K is difficult to be calculated for a given texture and different values could be found using the Eq.6

$$\lambda_{\text{poros sample}} \cong \left(1 - \frac{3}{2}\text{p}\right)(\lambda + \lambda_{\text{Rad}}) = \left(1 - \frac{3}{2}\text{p}\right)\left(\lambda_{\text{P}} + \frac{16\text{n}^2\sigma\text{T}_{\text{R}}{}^3}{3(\Gamma + \text{K})}\right) \tag{6}$$

where p is the total porosity. From Eq.5, it is obvious that the total thermal conductivity of a porous sample depends on the following λ_P, n, K, Γ and p. Note that these properties must be known at the operating temperature of the system, and that their values at high temperatures differ from the ones reported at room temperature. The data given in the next part are obtained at room temperature. Tables 1

Material	Porosity (%)	Refractive index	Thermal conductivity λ (W.m^{-1} K^{-1})	Mean absorption coefficient, K (cm^{-1})	Mean Scattering Coefficient, Γ (cm^{-1})
YSZ (electrolyte)	6(1) 0(2)	1.8(3)	2.3(1) 2.16(2)	2.6(1) 500(2)	100(1) 0(2)
LaMnO3 (cathode)	40(1) 30(2)	1.8(2)	0.8(1) 1.86(2)	10^{6}(1)	0(1)
Ni-YSZ (anode)	40(1) 40(2)	/	3.7(1) 5.84(2)	10^{4}(1)	0(1)

Table 1. SOFC Radiation proprieties.

(1)K.J. Daun, J. Pow. Sources, 2005
(2)S. Murthy, J. Pow. Sources, 2003
(3) D. Lee Damm, Ph. D Thesis, 2005

3. Mathematical model

The studied SOFC system is an anode supported SOFC configuration Fig 01. The electrolyte is in the form of a dense layer of polycrystalline yttrium-zirconia (ZrO2-8% Y2O3) and its thickness is 15 microns. The (30%) of lanthanum manganite of 75 micrometers~cathode is a porous layer, (40%) of nickel~thick and the anode is a porous cermet (zirconia-yttrium (50/50 mixture by weight) of 500 micrometers thickness. Based on the available data of the materials involved for the design of the heart of the cell, we can conclude that the electrolyte is optically thin in terms of radiation while both the cathode and the anode are optically thick. Furthermore, we assume that the radiation leaves the heart of the cell and it is distributed isotropically at both anode and cathode of the cell. Fig.1,

The fundamental equations governing the coupled transfer phenomenon in the study area are based on the following assumptions:
(1) All variables have constant values on each control volume;
(2) the only heat source considered is the heat source due to the ohmic resistance;
(3) The electrolyte of yttria-stabilized zirconia is considered as a medium optically thin throughout the temperature range of this study [873-1273 K].
Physical parameters and thermal properties is given in Table 02.

3.1. Electrolyte

Within the assumed dense electrolyte, energy is transported by two mechanisms related to conduction and thermal radiation. The transport equation also takes into account ohmic losses. The governing equation for the heat transfer in the electrolyte takes the following form ‘’Eq.7’’:

$$\underbrace{\frac{\partial T}{\partial t}}_{\text{Accumulation term}} + \underbrace{\frac{\partial}{\partial x}\left(\lambda_{eff,ele}\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda_{eff,ele}\frac{\partial T}{\partial y}\right)}_{\text{conduction term}} = \underbrace{\left[2k\sigma C_1+4\sigma T^3 e^{2kL}\frac{\partial T}{\partial x}\right]e^{2kx}+\left[2k\sigma C_2+4\sigma T^3\frac{\partial T}{\partial x}\right]e^{-2kx}}_{\text{radiation term}} + \underbrace{\frac{i}{\Gamma_{ele}}}_{\text{Ohmic source}} \tag{7}$$

From Eq.7, it is concluded that the radiative exchanges are more significant than the thickness of the electrolyte. The radiation term is obtained after applying the method of Schuster-Schwartzchild to two streams. This approximation is based on the fact that the radiation is considered as isotropic in the two hemispheres of dissemination. Modest Michael F. (2003) has shown that this problem could have an analytical solution, which could be treated as conducto-radiative transfer within a non-diffusing 1D planar geometry environment that is contained between two isothermal surfaces maintained at different temperatures. The heat flux exchanged through these surfaces is calculated from Eq.8:

$$q_{rad} = -\sigma\left(T_{top}^4 - T^4\right)e^{-2kx}e^{2kL} + \sigma\left(T_{bott}^4 - T^4\right)e^{-2kx} \tag{8}$$

3.2. Electrodes

Overall equation governing heat transfer in the electrodes; anode Eq.9 and cathode Eq.10, considers three modes of heat transfer: conduction, convection and radiation.

$$\underbrace{\rho C_p \frac{\partial T}{\partial t}}_{I} + \underbrace{\frac{\partial}{\partial x}\left(\left(\rho C_p u\right)_{fuel} T\right) + \frac{\partial}{\partial y}\left(\left(\rho C_p v\right)_{fuel} T\right)}_{II} = \underbrace{\frac{\partial}{\partial x}\left[\left(\lambda_{eff,an} + K_{R,an}\right)\frac{\partial T}{\partial x}\right] + \frac{\partial}{\partial y}\left[\left(\lambda_{eff,an} + K_{R,an}\right)\frac{\partial T}{\partial y}\right]}_{III} + \underbrace{\frac{i}{\Gamma_{an}}}_{IV} \tag{9}$$

$$\underbrace{\rho C_p \frac{\partial T}{\partial t}}_{I} + \underbrace{\frac{\partial}{\partial x}\left(\left(\rho C_p u\right)_{air} T\right) + \frac{\partial}{\partial y}\left(\left(\rho C_p v\right)_{air} T\right)}_{II} = \underbrace{\frac{\partial}{\partial x}\left[\left(\lambda_{eff,cath} + K_{R,cath}\right)\frac{\partial T}{\partial x}\right] + \frac{\partial}{\partial y}\left[\left(\lambda_{eff,cath} + K_{R,cath}\right)\frac{\partial T}{\partial y}\right]}_{III} + \underbrace{\frac{i}{\Gamma_{cath}}}_{IV} \tag{10}$$

The radiation heat flux exchanged across the two electrodes is considered isotropic and optically thick and it is obtained via the radiation conductivity ‘Rosseland equation’, Eq.11.

$$q_{rad} = -\underbrace{\frac{16n^2\sigma T^3}{3\beta_R}}_{K_R}\nabla T \tag{11}$$

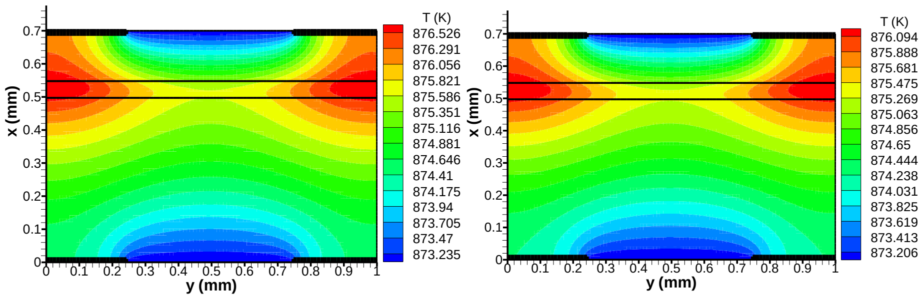
Symbol	**Unit**	**Cathode**	**Anode**	**Electrolyte**
C_P	[J kg^{-1}K^{-1}]	573	595	606
ρ	[kg/m^3]	6000	6200	5560
K	[m^2]	10^{-20}	10^{-20}	10^{-25}
ε	[%]	40	40	6
λ	[W/km]	02.00	02.00	02.00
e	[μm]	150.10^{-6}	500.10^{-6}	50.10^{-6}

Table 2. Physical parameters and thermal properties and heat radiation

4. Results

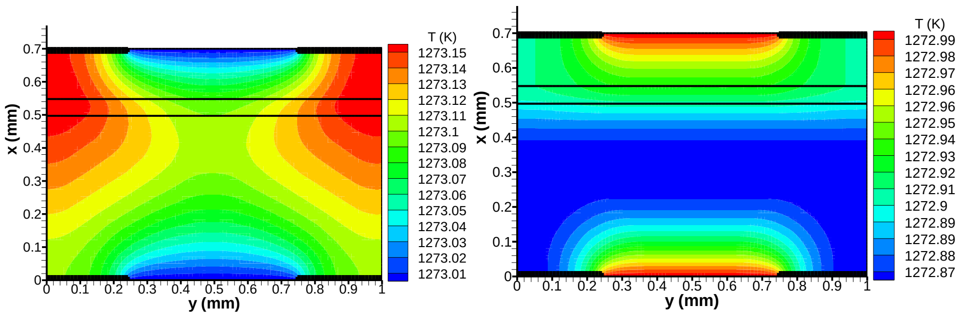
4.1. Operating temperature effect on PEN-SOFC-AS

Two different temperature values are examined: an intermediate temperature of 873K and a high temperature of 1273K. For the intermediate temperature 873K and in absence of radiation effects, the temperature fields are attributed to the diffusion phenomenon and the maximum temperature is located at the electrolyte approximately 876.52K. When the effect of radiation is considered the thermal diffusion increases leading to the reduction of the maximum temperature at 876.09K. Fig.2, Fig3.



(a) (b)

Fig. 2. PEN-temperature SOFC-AS fields at T = 873K (a) Without radiation, (b) with radiation



(a) (b)

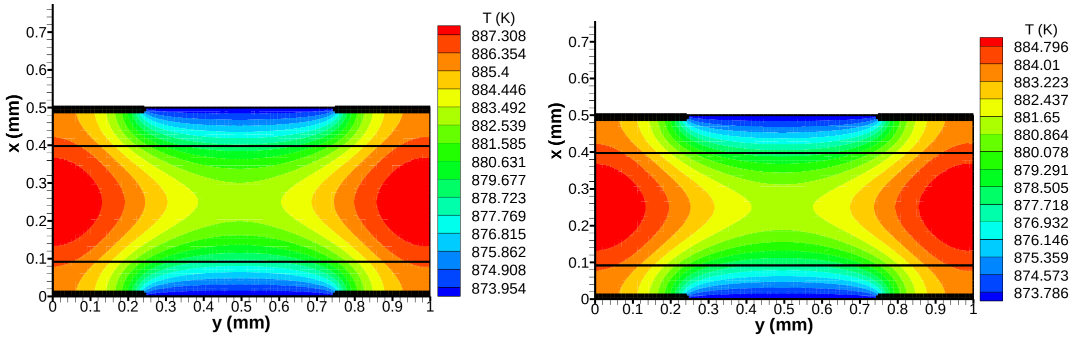
Fig. 2. PEN-temperature SOFC-AS fields at T = 1273K (a) Without radiation, (b) with radiation

4.2. Operating temperatureat effect at PEN-SOFC-ES

At the intermediate temperature (873K) and when the effects of the thermal radiation are not considered it is found that the temperature field shows an important raise of temperature which approaches the 887.308K and it is located at the electrolyte of the PEN-SOFC. This increase is due to the ohmic overpotential and the increase of the electrolyte thickness. The energy dissipation due to the Joule effect is significant.

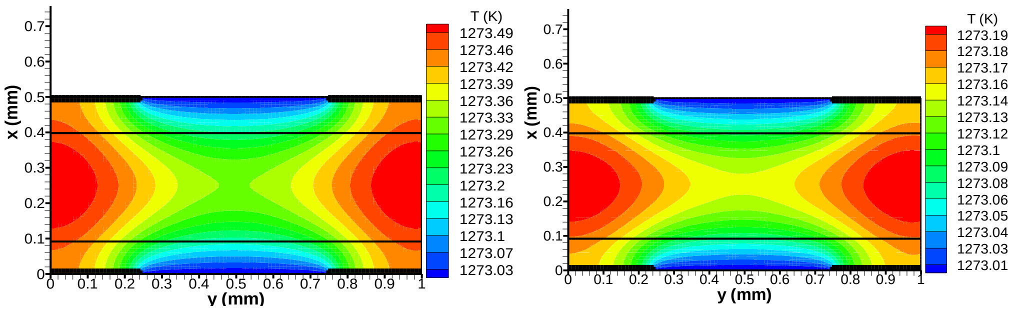
The thermal radiation effects presence reached a maximum temperature value of 884.796 K. A significant decrease in temperature of 3.49K is caused by radiation transfer Fig. 4, Fig. 5. At high operating temperatures (1273K) and ignoring the thermal radiation effects, the temperature fields show a slight increase in temperature due to the ohmic overpotential. The maximum temperature reached by the cell is 1273.49K. This temperature is distributed over a large part in the electrolyte at the electrolyte supported configuration. This low temperature rise is due to the thermal agitation phenomenon caused by the high operating temperatures. The presence of thermal radiation effects reduce the maximum temperature up to

1273.19 K with decreasing the surrounding temperature by 0.68K and 0.3K, which is caused due to the radiation transfer. . Fig.4, Fig5



(a) (b)

Fig. 2. PEN-temperature SOFC-ES fields at T = 873K (a) Without radiation, (b) with radiation



(a) (b)

Fig. 2. PEN-temperature SOFC-ES fields at T = 1273K (a) Without radiation, (b) with radiation

5.Conclusions

In the present work the effect of the heat radiation transfer on the temperature distribution in a PEN-SOFC was studied by the aid of a mathematical model. It was found that at intermediate temperatures the presence of heat is attributed mainly to the ohmic resistance and the the migration of O2- ions. The electrons movement and the contact resistance between the electrolyte and the electrodes led to an important raise of the temperature. In this case the effect of the radiation transfer on the temperature of the cell was minor. At high operating temperatures, the effect of the thermal agitation significantly reduced the temperature raise due to the ohmic source. In the later case, the effect of thermal radiation was significant on the temperature field and the spatial temperature distribution. But its effect on the overall temperature of the cell can be neglected. Moreover, the effect of the geometrical parameters was clearly obtained. It was found that the thermal radiation effects were more significant at the geometric configuration of the electrolyte-supported SOFC PEN-ES that in the case of the anode-supported SOFC PEN-AS. Furthermore, it was found that the current density was proportional to the ohmic source and the heat generation due to Joule effect. By increasing the ohmic source its effect on the thermal radiation and the temperature gradient was increased.

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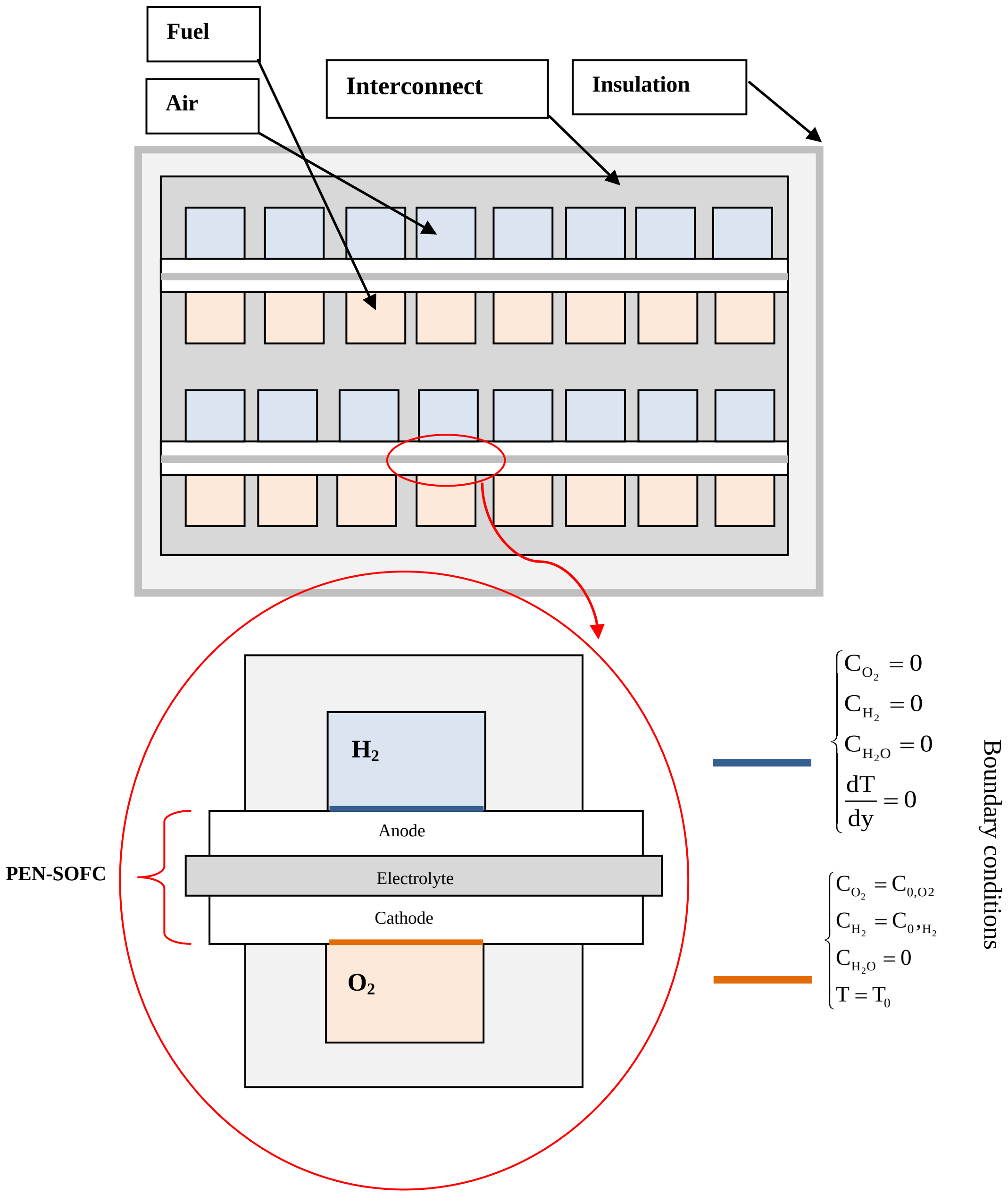

Fig.1. Study area presentation and boundary conditions at heart cell