Numerical Study of Solid Oxide Fuel Cell Performance with Helical and Serpentine Flow Field Designs

Mohamed E. Saied, Khaled I. Ahmed, Mahmoud A. Ahmed, Mahmoud M. Nemat-Alla and Mohamed G. El-Sebaie

Abstract—Solid Oxide Fuel Cell (SOFC) is preferred for its high efficiency and stability and its low emission and cost. The current work investigate, numerically, the performance of the helical and serpentine channel designs, commonly used with Proton Exchange Membrane (PEM). A comprehensive 3D CFD numerical model is developed, using Fluent 14.5.7. The model is then validated using one of the available experimental results from previous researches. The comparison between the numerical model and the reported experimental results shows very good agreement. In the presents study, the effect of the channel design shape on the cell performance is investigated. The velocity distribution through the anode and cathode channel and the potential and current density distributions through the cell are presented. The results show that the studied two configurations of the channel design have the same cell performance. The results show backflow in the cathode outlet in both configurations. This leads to a future work of increasing the number of inlets to increase the inlet flow rate.

Keywords—CFD, Channel design, Fluent, PEM, Solid oxide fuel cell.

I. INTRODUCTION

Fuel cell is a device that consists of anode, electrolyte and cathode and used for generation of electricity by the chemical reaction between hydrogen (fuel) and oxygen where a reduction for the hydrogen atoms occur at the anode side producing a hydrogen ion and electrons. Electrons passes through an external circuit to the cathode side where oxidation occurs for the oxygen atom producing oxygen ions that react with the hydrogen (fuel) ions producing water vapour, so is counted as a clean energy generator device. Both fuel and oxygen is supplied to the cell from out. In addition, anode, cathode and electrolyte there are two top plates called current collector that contain channels for passing the fuel and oxygen through the cell [1]. The cell performance depends on the shape of the channel design, i.e. the current collector design. In the previous studies cross and co-Flow design are discussed [2]. In the current study, Helical and serpentine flow field design as shown in figure 1 will be discussed. The pervious designs [2-3] didn’t allow the full utilization of the fuel flow rate as the fuel passage is quite short so amount of the fuel will migrate without reactions, on the contrary the helical and serpentine shaped flow field will allow the largest possible use of the fuel as the flow passage is long and the flow is allowed to spread over whole surface of the cell as shown in figure 1. The presented study is carried out to study the performance of the cell with helical and serpentine flow channel for this aim The ANSYS FLUENT CFD version 14.5.7 is used to solve the mass and energy conservation and the FLUENT add-on SOFC MODULE to solve the electrochemical reactions and over-potential parameter through the presented cell.

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Fig. 1 Flow Field shape: (a) Helical; (b) Serpentine
II. MODEL GEOMETRY

Figure 2(a) and figure 2(b) show the SOFC configuration for helical and serpentine flow field design respectively where the cell consists of anode, electrolyte and cathode besides the two current collector plates where the flow channel is created. Figure 3 show the mesh used for the current study. The computational model is divided into more than 2 million cells (control volume) where the hexahedron element is used for the generation of the mesh. The mesh scheme is controlled to be finer in the electrolyte, anode and cathode and quite coarse in the current collector and channel. Table 1 presents used model dimensions. [4].

III. MATHEMATICAL EQUATIONS

The mathematical model is solved using the add-on SOFC module built in ANSYS FLUENT [5] and the reference parameters that used for electrochemical reactions are summarized in Table 2. [2, 4-5]. This section discusses the model parameters based on ANSYS FLUENT fuel cell module manual [5, 6-7]. The transport of gas mixtures in the gas channels and in the electrodes conforms to the mass, momentum, species conservation principles, and electrochemical reactions.

Table 1. Used model dimensions

<table>
<thead>
<tr>
<th>Item</th>
<th>mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell Length</td>
<td>19</td>
</tr>
<tr>
<td>Cell Width</td>
<td>19</td>
</tr>
<tr>
<td>Channel width</td>
<td>1</td>
</tr>
<tr>
<td>Channel height</td>
<td>1</td>
</tr>
<tr>
<td>Anode layer thickness</td>
<td>0.7</td>
</tr>
<tr>
<td>Cathode layer thickness</td>
<td>0.05</td>
</tr>
<tr>
<td>Electrolyte thickness</td>
<td>0.01</td>
</tr>
<tr>
<td>Interconnect height</td>
<td>1.5</td>
</tr>
</tbody>
</table>

The 3D fluid flow and heat transport is solved using CFD techniques, which include conservation of mass, momentum and energy that can be expressed in the Navier-Stokes equations written as follows:

\[
\frac{\partial}{\partial t} \int \rho \phi dV + \oint \rho \phi V \cdot dA + \oint \Gamma \phi \nabla \phi \cdot dA = \int S \phi dV \quad (1)
\]

The conservation equation in this form states that the rate of change quantity \( \phi \) plus the transport due to convection plus the transport due to diffusion is equal to the source. \( \phi \) is the transported quantity (energy, momentum), \( t \) is time, \( A \) is the surface area, \( V \) is volume, \( \Gamma \phi \) is the diffusivity coefficient, \( S \) is the source term. Equations for the surface over-potential, the driving force behind the electrochemical reactions within the fuel cell simulation, are solved according to the following two equations

\[
\nabla \cdot (\sigma_{sol} \nabla \phi_{sol}) + R_{sol} = 0 \quad (1)
\]

\[
\nabla \cdot (\sigma_{mem} \nabla \phi_{mem}) + R_{mem} = 0 \quad (2)
\]

The first equation describes the difference between the phase potential of the solid materials which governs the transport of electrons through the GDL porous material and current collectors. The second equation describes ionic transport of \( H^+ \) ions through the membrane. \( \sigma \) represents the electrical conductivity (1/Ωm); \( \phi \) is the electric potential (volts); \( R_{sol,mem} \) is the volumetric transfer current (A/m³) in the solid or membrane. Transfer currents are computed within the catalyst layers using the Butler-Volmer function.

\[
R_{an} = \gamma_{an} \left( \frac{H_2}{H_2} \right) \gamma_{an} \left( e^{\frac{d_{an}F_n}{RT}} - e^{\frac{d_{cat}F_n}{RT}} \right) \quad (3)
\]
\[ R_{cat} = \frac{1}{\gamma_{ref}} \left( \sum_{i}^{N} \left( \frac{O_2}{O_2}_{ref} \right)^{\gamma_{cat}} \left( e^{\frac{\sigma_{cat} F \phi_{cat}}{RT}} - e^{\frac{\sigma_{an} F \phi_{cat}}{RT}} \right) \right) \] (4)

Where \( \xi \) is the specific active surface area \((m^2)\), \( j_{ref} \) is the reference exchange current density per active surface area \((A/m^2)\). The quantities in the brackets represent the local species concentration \((Kmol/m^3)\). \( \gamma \) is the concentration dependence; \( \sigma \) is the transfer coefficient. \( F \) is Faraday's constant and \( R \) is the universal gas constant. The quantity \( \eta \) is the local surface over-potential or activation loss which is computed using the following equations where \( V_{oc} \) is the open circuit voltage

\[ \eta_{an} = \phi_{sol} - \phi_{mem} \] (5)
\[ \eta_{an} = \phi_{sol} - \phi_{mem} \] (6)

Mass conservation is obeyed using volumetric species mass terms.

\[ S_{H_2} = - \frac{M_{H_2}}{2F} R_{an} < 0 \] (7)
\[ S_{O_2} = - \frac{M_{O_2}}{2F} R_{cat} < 0 \] (8)
\[ S_{H_2O} = - \frac{M_{H_2O}}{2F} R_{cat} > 0 \] (9)

Where \( S_k \) represents the species source term \((Kg/s.m^3)\); \( M_{k} \) is the molecular mass of the species \((kg/kmole)\). The sign of the equations indicate that hydrogen and oxygen are consumed while \( H_2O \) is generated. The electric current is conserved by obeying the following equation.

\[ \int_{an} R_{an} dV = \int_{cat} R_{cat} dV \] (10)

Volumetric sources for thermal energy are required because not all of the chemical energy is converted to electrical work. This is accounted for by using a thermal energy (rate of enthalpy change, \( S_k \)) equation

\[ \dot{h} = h_{react} - R_{an,cat} \eta_{an,cat} + 1/2R_{ohm} + h_L \] (11)

Where \( h_{react} \) is the net rate of enthalpy change \((J/s)\) due to the electrochemical reactions. \( R_{an,cat} \eta_{an,cat} \) is the product of the transfer current and the over-potential in the anode or cathode. \( R_{ohm} \) is the ohmic resistivity of the conducting media and \( I \) is the current \((A)\). \( h_L \) is the rate of enthalpy change due to phase changes of the water.

Flow within the porous media of the GDLs and catalyst layers is modelled by adjusting the source term by adding a negative source which represents fluid flow pressure drops in the species equations and calculating species.

\[ S_i = - \left( \frac{\mu}{k} v_i + C_2 \frac{1}{2} \rho v_{mag} v_i \right) \] (12)

Si indicates the source in i direction. \( \mu \) is the kinematic viscosity \((m^2/s)\), \( \rho \) the fluid density \((kg/m^3)\), \( v_i \) and \( v_{mag} \) are the velocity and magnitude of the velocity \((m/s)\), \( C2 \) is the inertial resistance factor \((m-1)\).

### Table 2. Reference parameters for electrochemical reactions.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anode exchange current density</td>
<td>10</td>
<td>( A/m^2 )</td>
</tr>
<tr>
<td>Cathode exchange current density</td>
<td>20</td>
<td>( A/m^2 )</td>
</tr>
<tr>
<td>Anode concentration dependence</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>Cathode concentration dependence</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Anode porosity</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>Cathode porosity</td>
<td>0.3</td>
<td></td>
</tr>
</tbody>
</table>

### IV. INPUT PARAMETERS AND BOUNDARY CONDITIONS

Anode and cathode boundary conditions are set as reactant species velocities at the inlets to model the momentum transport. Reactant species mass fraction boundary conditions are applied at the inlets and outlets for modelling the mass transport and diffusion phenomena. The motivating force for the development of the electric current is the applied electric potential difference between the anode and cathode electrodes. The anode voltage is set to zero (grounded) and the cathode voltage is set as the cell operating voltage that takes various volt starts from open circuit voltage. Polarization curves are obtained by setting the cell voltage at constant value, solving the model, and integrating the local current density value along the active layer, which gives the cell current density.

The cell working conditions and properties of the model parts are presented in Tables 3 and 4. [4-5].

In the numerical analysis setup, the voltage at the anode current collector top surface is set to zero and is set to the cell operating voltage at the cathode current collector top surface. All other external walls are insulated.

### V. SIMULATION RESULTS AND DISCUSSION

Figure 4 below shows the cell polarization curve obtained from the current study for helical, serpentine shaped flow field and the experimental results [4]. The results show a good agreement between the simulation and the experimental results up to cell current density of 1A cm\(^{-2}\) and a small deviation is occurred at higher current densities with a maximum deviation 9.7% at 0.6 volt compared to 11% deviation for the counter-flow design [4]. Also the I-V curve shows a good agreement in the calculated results for both helical and serpentine design. The deviation between the calculated and experimental results is due to inaccurate gases and porous media properties, errors in computations, Assumptions for the solid oxide fuel cell modelling and errors in the calculations of the polarization concentration.
Table 3, Working conditions of SOFC model.

<table>
<thead>
<tr>
<th>parameter</th>
<th>Boundary condition</th>
<th>Temperature (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen inlet</td>
<td>Mass flow inlet (kg/s)</td>
<td>1.141 x 10^-8</td>
</tr>
<tr>
<td>Oxygen inlet</td>
<td>Mass flow inlet (kg/s)</td>
<td>2.287 x 10^-7</td>
</tr>
<tr>
<td>Hydrogen outlet</td>
<td>Pressure outlet</td>
<td>Convection</td>
</tr>
<tr>
<td>Oxygen outlet</td>
<td>Pressure outlet</td>
<td>Convection</td>
</tr>
<tr>
<td>Terminal anode collector</td>
<td>Wall</td>
<td>Adiabatic</td>
</tr>
<tr>
<td>Terminal cathode collector</td>
<td>wall</td>
<td>Adiabatic</td>
</tr>
<tr>
<td>Cell surroundings</td>
<td>wall</td>
<td>Adiabatic</td>
</tr>
</tbody>
</table>

Table 4, Material Properties of different components of the cell.

<table>
<thead>
<tr>
<th>parameter</th>
<th>Anode</th>
<th>Cathode</th>
<th>Current collector</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg/m³)</td>
<td>4760</td>
<td>4640</td>
<td>4640</td>
</tr>
<tr>
<td>Specific heat (J/kg-k)</td>
<td>377</td>
<td>377</td>
<td>300</td>
</tr>
<tr>
<td>Thermal conductivity (w/m-k)</td>
<td>11</td>
<td>2.37</td>
<td>2.2</td>
</tr>
<tr>
<td>Electrical conductivity (1/ohm-m)</td>
<td>28586.2</td>
<td>12098</td>
<td>4,000,000</td>
</tr>
</tbody>
</table>

Flow Field velocity Distribution

Figure 5 and Figure 6 show the velocity distribution for the case of 0.8 volt at the anode and cathode channel for both Helical and serpentine flow field design. Figure 5(a) and figure 6(a) show the velocity distribution through the anode channel. The velocity increases gradually through the channel reach a maximum value at the anode outlet. The increasing in velocity is due to the generation of water vapor (H₂O) that produced from the electrochemical reactions occurred at the cell. For the velocity in the cathode channel, the velocity is decreased gradually from inlet to outlet due to the consumption of the oxygen in the electrochemical reactions as shown in figure 5(b) and figure 6(b).

It is obvious that the maximum values occur at the interface between the cathode surface and current collector in which, the produced electrons pass through the shortest way to the outer surface of the cell and then to the external circuit. The distribution of the current density is uniform through the cell as shown in figure 6 this mean that the chemical reactions occur at all the active area of both electrode and did not decrease by the consumption of the fuel so the best use of the fuel is achieved.

The velocity distribution values for the serpentine design is less than the velocity distribution values for helical design and this due to that the amount of electrochemical reactions occurred at the serpentine design is more than the reactions at the helical design and this is obvious from the polarization curve (figure 4) and the current density distribution at figure 7.

Pressure Distribution

Figure 7 and Figure 8 show the pressure distribution for the case of 0.8 volt through fuel and oxygen channel for both serpentine and helical design.it is obvious from figure 7(a) and 8a) that the pressure is high at the first passage and decreased gradually through the anode channel. This because of that the velocity is increased gradually through the channel from inlet to outlet due to the generation of water that produced from the electrochemical reactions.

For the pressure distribution through the cathode channel as shown in figure 7(b) and 8(b), the pressure is increased gradually form inlet to outlet as the velocity is decreased gradually through the cathode channel as the oxygen is consumed in the electrochemical reactions.

The pressure distribution at the serpentine anode channel is higher than the pressure distribution for the helical design due to that the velocity distribution values at the helical anode channel is more than the velocity distribution values for serpentine flow channel.

Current density distribution

Figure 9 and Figure 10 show the distribution of the current density for both Helical and Serpentine design for the case of 0.8 volt.
Fig. 4 Velocity distribution for: (a) Serpentine anode channel; (b) Serpentine cathode channel.

Fig. 5 Velocity distribution for: (a) helical anode channel; (b) helical cathode channel.

Fig. 6 Pressure distribution for: (a) Serpentine anode channel; (b) Serpentine cathode channel.
VI. CONCLUSION

In the current study, two flow field designs for the solid oxide fuel cell are presented. The aim of this study is to discuss the performance of the cell with change in the flow field design. The polarization curve, velocity distribution, the pressure distribution, and the current density distribution are also presented. It is found that the new design for the flow field design is in agreement with the experimental data at the same conditions and it gives small deviations about 9.7% from the experimental data compared to 11% deviation for the counter-flow design [4]. The results also show that a backflow in the cathode outlet in both studied designs. A future work of increasing the number of inlets to increase the inlet flow rate is required.

Acknowledgment

The author is obliged to Assuit University, Assuit, Egypt for providing valuable resources to carry out this study.

Fig. 7 Pressure distribution for: (a) helical anode channel; (b) helical cathode channel.

Fig. 8 Distribution of current density for: (a) serpentine design at xy plane of z=1.515 mm; (b) serpentine design at zx plane of y=9.5 mm.
Fig. 9 Distribution of current density for: (a) helical design at xy plane of z=1.515 mm; (b) helical design at zx plane of y=9.5 mm.

REFERENCES


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