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Performance evaluation of different bipolar plate designs of 3D planar anode-supported SOFCs

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ABSTRACT

The performance of Solid Oxide Fuel Cells (SOFCs) is highly sensitive to the fluid dynamics, the interfacial areas, and the residence time of the gases. These parameters are primarily dictated by the geometry of the channels carrying the fuel and the oxidant. However, not many investigations have been made to study the effect of bipolar plate designs on cell performance. We report a detailed comparative study of the performance characteristics of straight and serpentine channel geometries. Simulations of these two channels have been made taking into account fluid flow through the channels and the porous electrodes, multicomponent diffusion, heat transfer, charge transfer reaction kinetics and electrodynamics. Performance of each channel has been compared to in-house experimental data. Extensive parametric analyses have been carried out to evaluate the dependence of cell performance on fuel and air flow rates. Favourable operating ranges of hydrogen and air feeds have been estimated analytically taking into account fuel utilisation, cell temperature, channel pressure drops, and current density. It has been shown that serpentine geometries offer remarkably more uniform distribution of ionic current density, and significantly higher power output and fuel utilisation compared to straight channel geometries. However, these are accompanied by a penalty of pressure drop. This analysis can provide a useful guideline for selecting the channel geometry.

1. Introduction

As research and development around the world focuses on the need for low-emission, sustainable, and cost-efficient alternatives to conventional sources of energy, the Solid Oxide Fuel Cell (SOFC) emerges as a promising possibility. Compared to the overall efficiency of 35% or less for a traditional thermal power plant [1], SOFCs can reach much higher efficiencies of 45–60% [2] depending on their design and operating conditions. Moreover, the fuel flexibility of an SOFC, particularly its capacity for internal reforming of most carbonaceous fuels, and the prospect of combined heat and power generation make it a compelling candidate to meet the future world's energy demands in an environment friendly fashion.

An SOFC is a device that converts chemical energy (primarily from hydrogen) directly into electrical energy by means of electrochemical catalytic reactions. Unlike most other varieties of fuel cells, SOFCs do not need expensive catalysts. Fig. 1 shows a schematic diagram of a planar anode-supported SOFC comprising of a dense electrolyte membrane sandwiched between a positive and a negative porous electrode. Channels are laid on either side of the membrane-electrode assembly (MEA) to construct a single SOFC unit cell which is fed with fuel (usually hydrogen or synthesis gas) on the anode side and oxidant (oxygen or air) on the cathode side. The boundaries shared by the anode and cathode with the electrolyte, frequently referred to as Triple Phase Boundaries (TPBs), are the site of electrocatalytic reactions that generate current. Each TPB consists of an ionic phase, an electronic phase, and pores. Fuel diffuses through the anode microstructure to reach the anodic TPB, where it oxidises to liberate two electrons which travel via the outer circuit to the cathode electrode. Oxygen/air diffuses through the cathode and gets reduced to O^{2-} at the cathodic TPB. The electrolyte, being an electronic insulator but an ionic conductor, is responsible for the transport of O^{2-} ions over to the anode side, where they react with H^{+} ions to produce water, generating an ionic current that completes the circuit [2]. Schematics of reaction mechanisms at various interfaces of the MEA are shown

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Nomenclature

ρ	Density, kg/m^3
$\mathbf{u}$	Velocity, m/s
p	Pressure, Pa
I	3×3 identity matrix
μ	Dynamic viscosity, kg/(m s)
$\mathbf{F}$	Body force, kg m/s
ϵ_p	Porosity
κ	Permeability, m^2
Q_{br}	Mass flow rate, kg/s
$\partial\Omega$	Control surface, m^2
Q_{vol}	Volumetric flow rate, *SCCM*
$\mathbf{j}$	Diffusive mass flux, kg/(m^2 s)
ω	Weight fraction
R_i	Mass flux due to reaction, kg/(m^2 s)
x	Mole fraction
T	Absolute temperature, K
M	Molecular weight, kg/mol
k	Thermal conductivity, W/(m K)
q	Heat flux, W/m^2
C_p	Specific heat at constant pressure, J/(kg K)
τ	Viscous stress tensor, Pa
Q_e	Heat flux due to reaction, W/m^2
i_v	Local current density, A/m^2
S_g	Specific surface area, 1/m
i_0	Exchange current density, A/m^2
C	Molar concentration, mol/m^3
α	Charge transfer coefficient
n	Number of electrons (transferred during reaction)
F	Faraday constant, A s/mol
η	Overpotential, V
σ	Ionic conductivity, S/m
Φ	Electrode/electrolyte potential, V
Q_m	Heat flux due to Joule heating, W/m^2
U_f	Fuel utilisation factor

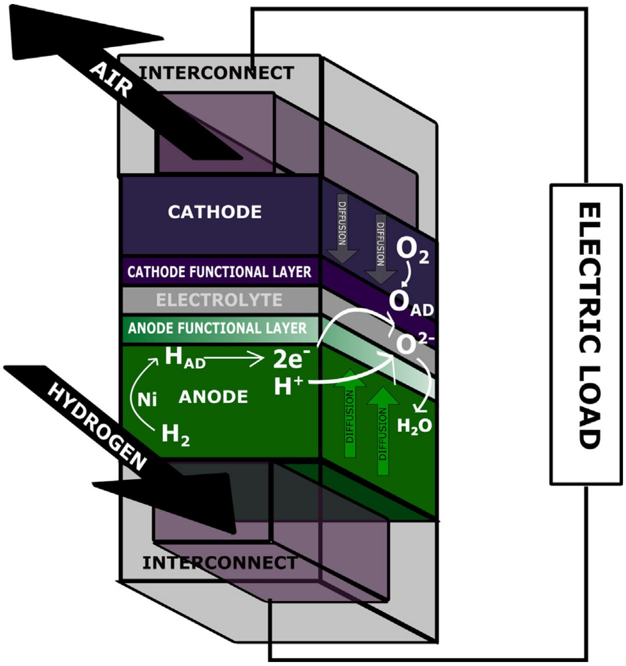

Fig. 1. Schematic diagram of a solid oxide fuel cell.

in Fig. 1. The overall electrochemical reactions prevalent in different electrodes are summarized below:

$$\textit{Anodic Reaction}: H_2 \rightleftharpoons H^+ + 2\,e^- \tag{1}$$

$$\textit{Cathodic Reaction}: O_2 + 2e^- \rightleftharpoons 2\,O^{2-} \tag{2}$$

$$\textit{Overall Reaction}: 2H^+ + O^{2-} \rightleftharpoons H_2O \tag{3}$$

At chemical equilibrium, the potential difference (also known as the Nernst potential) based on the aforementioned electrochemical reactions arises from the overall change in Gibb's free energy change and tends to be around 1.1–1.2 V. As the cell is driven away from equilibrium, the actual voltage varies depending on the operating temperature and the partial pressure of oxygen at the reactive interfaces [2]. For practical operation, multiple SOFC unit cells are usually stacked together in series to develop a higher potential and to draw usable electric power, with successive MEAs separated by bipolar plates. The bipolar plates are primarily made of ferritic grade steel as applicable for intermediate-temperature SOFCs [3] and comprises of fluid flow channels and current-collecting ribs [4]. The key challenge when it comes to SOFC stack operation is to optimise the drawable power with a good fuel utilisation while ensuring maximum energy efficiency and minimal thermal and electrical fatigue for a given cell stack volume. This calls for an appropriate design of the bipolar plates, particularly the flow passages. Depending on the materials used, operating conditions, and design, the overall performance of the cell may be limited by factors like catalytic properties of the electrode materials, the ionic conductivity of the electrolyte, and constraints in diffusion of gases from the flow channels to the TPBs [5]. Given the complexity of the physics and the geometry of an SOFC, it is often a formidable task to gather experimental data pertaining to the flow, transport, or thermodynamic conditions prevalent inside a stack during operation. Modelling and simulation is hence, a promising way of gaining insights into ways of optimizing SOFCs as commercially realisable energy sources.

While instances of fuel cell modelling studies go back to the 1990s, limitations in computational capacity has mostly kept comprehensive models restricted to one- or two-dimensional numerical studies for several years [6–11]. In recent times, however, multiple studies have investigated several aspects of fuel and electrolyser design in three dimensions through CFD simulations [12–23]. Extensive investigations on SOFC performance, geometry, efficiency have also been carried out. For instance, Andersson et al. [21] did a comparative study of three distinct straight channel geometries. Tseronis et al. [24] have done a non-isothermal time-dependent analysis of the behaviour of planar SOFCs. Lee et al. [17] did a thorough analysis of the effect of fuel utilisation in a single straight channel. Choudhary and Sanjay [19] have carried out a CFD analysis of various flow configurations in a straight-channel SOFC plate with internal reforming. A detailed literature review of various endeavours towards SOFC design and performance optimisation has been carried out by Ramadhani et al. [25]. The review brings out that studies focussing on the effect of bipolar plate channel geometries on the performance of SOFCs are rare in available literature.