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A new modified-serpentine flow field for application in high temperature polymer electrolyte fuel cell

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HIGHLIGHTS

- Compensated serpentine geometry is proposed to improve the distribution in HT-PEFC.
- Simulation results show higher uniformity index values compared to serpentine design.
- The new design shows performance improvement of ~27% at operating voltage of 0.57 V.
- A CDMD is developed and tested in the fuel cell for experimental validation.
- The experimental and simulation data agree well with the mismatch factor about ±4%.

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ABSTRACT

Flow field design for the distribution of reactants and products on the electrode surface plays an important role in the overall performance of the fuel cell. It acts as a crucial factor when the laboratory scale fuel cell is scaled up for commercial applications. In the present work, a novel flow field design is proposed and its usefulness for the fuel cell applications are evaluated in a high-temperature polymer electrolyte fuel cell. The proposed geometry retains some of the features of serpentine flow field such as multiple bends, while modifications are made in its in-plane flow path to achieve comparatively uniform reactant and product distribution. A three-dimensional CFD model is developed to analyze the effectiveness of the proposed flow field. An HT-PEFC is fabricated and experimented with the proposed flow field for experimental validation. Furthermore, a low-cost current distribution mapping device is developed to validate the current density distribution on the electrode obtained from the CFD model. It exhibits a mismatch of 4% in the spatial distribution of current density between the modelling and experimental results. The proposed design is capable of achieving higher uniformity in current distribution across the active area (0.998 for modified serpentine and 0.96 serpentine) compared to serpentine flow field. This aids in boosting the current density of the cell by 27% at 0.57 V operations.

1. Introduction

Fuel cells are considered as one of the potential future key technologies suitable for cleaner and efficient energy conversion. In the last two decades, a new generation of fuel cells called high-temperature polymer electrolyte fuel cell (HT-PEFC) has emerged as a subject of intensive research and development. The usage of phosphoric acid doped polybenzimidazole (PBI) membrane has been a highlight of this technology, allowing the elevation of the operating temperatures in the range ~120 to 180 °C. This leads to some distinct operational advantages, in comparison with the sulphonated membrane based electrolyte. Notable amongst them is the absence of complex water management issues, lower susceptibility to carbon monoxide (CO) poisoning, ease of thermal management and better electrochemical kinetics [1]. It has been reported by Krishnan et al. that these fuel cells can tolerate as much as 1 vol% CO without sacrificing the performance at 210 °C [2,3]. Due to its ability to tolerate higher CO in the fuel mixture, these fuel cells can be directly fed with reformed hydrogen by reforming hydrocarbons [4–7] eliminating precious metal catalyst based purifications. Furthermore, studies on these fuel cells have revealed that they can be operated in combined heat and power mode (CHP); reaching higher efficiencies (~87%) [8]. Even though the conversion efficiency of HT-PEM is slightly lower compared to LT-PEMFC, a reduced balance of plant leads to comparable

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Nomenclature

BPP	bipolar plate
CC	current collector
CDMD	current distribution measurement device
CFD	computational fluid dynamics
CHP	combined heat and power
CO	carbon monoxide
EIS	electrochemical impedance spectroscopy
FEM	finite elements method
FVM	finite volume method
GDL	gas diffusion layer
HT-PEFC	high-temperature polymer electrolyte fuel cell
LT-PEFC	low-temperature polymer electrolyte fuel cell
MEA	membrane electrode assembly
ORR	oxygen reduction reaction
PBI	poly-benzimidazole
PCB	printed circuit board
PEFC	polymer electrolyte fuel cell
SIMPLE	semi-implicit method for pressure linked equations
RAM	random access memory
UDF	user defined functions
UI	uniformity index

Symbols

α	permeability, m^2
α_k	charge transfer co-efficient
$A_{electrode}$	active area, m^2
A_{seg}	area of each segment of CDMD, m^2
C_p	specific heat, J kg^{-1}, K^{-1}
$C_{O_2}^{ref}$	reference concentration of oxygen, mol m^{-3}
C_{O_2}	local concentration of oxygen mol m^{-3}
D_i	binary diffusivity, m^2 s^{-1}
D_i^{eff}	effective diffusivity, m^2 s^{-1}
E_A	activation energy, J mol^{-1}
ε	porosity
F	Faraday constant, C $kmol^{-1}$
J_c	local current density, A m^{-2}
J_i	diffusive flux of ith reactant
$J_{c,T}$	reference current density at cathode at at temperature T, A m^{-2}
$J_{0,ref}$	reference current density at reference temperature, A m^{-2}
$J_{C,avg}$	average current density over the active area, A m^{-2}
J_C^k	current density measured on k-th segment of CDMD, A m^{-2}
J_V	volumetric current density, A m^{-3}
k_{eff}	effective thermal conductivity, J s^{-1} m^{-1} K^{-1}
λ	stoichiometry co-efficient
$\dot{m}$	mass flow rate, kg s^{-1}
M_i	molecular weight of i^{th} species, kg $kmol^{-1}$
MW_{O_2}	molecular weight of oxygen, kg $kmol^{-1}$
$\eta_{act,c}$	cathode local activation overpotential, V
n	number of electrons per mole of reactant, mol^{-1}
P	pressure, Pa
R	real gas constant J K^{-1} mol^{-1}
R_{tot}	total internal area specific electrical resistance, Ω m^2
R_{mem}	area specific resistance of membrane
$R_{con}(T)$	area specific contact resistance, Ω m^2
$R_{CDM}(T)$	area-specific resistance of CDMD, Ω m^2
ρ	density, kg m^{-3}
S_i	species source term, kg m^{-3} s^{-1}
S_T	energy source term, J m^{-3} s^{-1}
ΔS	entropy change, J K^{-1}
T	temperature, K
T_{ref}	reference temperature, K
t_{con}	interfacial separation at the planes engaged at the contact, m
$t_{electrode}$	thickness of the electrode, m
t_{mem}	thickness of the membrane, m
$\bar{u}$	velocity, m s^{-1}
μ	viscosity, Pa s
V_{OC}	open circuit voltage, V
V_{OP}	operating voltage, V
Y_i	species mass fraction

overall efficiency values [9]. On the downside, there is a significant amount of time and energy involved in starting up these fuel cells from room temperature. Researchers have studied different methods in order to formulate a suitable warm up strategy for these fuel cells [10,11]. The issue of phosphoric acid leaching and uptake in the porous bipolar plates over a period of time are important aspects which need attention to ensure longer durability [12]. The loss of acid from membrane electrode assembly (MEA) manifests in the form of a higher ohmic drop and increase in oxygen reduction overpotential in the cell performance characteristics [13]. At the catalyst layer, degradation due to agglomeration and sintering of the catalyst has also been reported by some researchers [14].

As of present, the reported flow fields which have been conceived for application in the field of fuel cells are numerous. Some of the options include serpentine, parallel, pin-type, integrated, spiral, bio-inspired and porous flow fields [15–19]. A particular geometry possesses a number of parameters such as channel width, depth, the shape of cross-section, the number of turns/channels, taper ratios, and path length [20–24]. These can be optimized as per the performance requirements. Other options include arranging reactant and oxidant distribution in these flow fields in co-flow or counter-flow mode. Computational Fluid Dynamics (CFD) can be used as a tool to identify the potential of different designs as evident from the numerous successful applications in LT-PEFCs [25–27]. Comparatively, fewer works based on CFD has been reported in the field of HT-PEFCs. Su et al. performed one of the earliest simulations on the performance of a PEFC above 100 °C using CFD, albeit the electrolyte was not phosphoric doped PBI [28]. To study the effect of cell temperature and porosity on the performance, a 2D single phase model was proposed by Sun et al. Their results show that gas diffusion layers (GDLs) possessing higher porosity can assist in improving performance [29]. A numerical model using finite element method (FEM) has been used by Thomas et al. to evaluate an open cathode flow field configuration. The cell design was found to reduce the overall stack volume and eliminate the requirement of a separate cooling manifold [30]. A 3D, steady state model for an HT-PEFC possessing phosphoric doped PBI membrane was put forward by Lobato et al. [31]. Their aim was to compare the performance for serpentine, parallel and pin type geometries for a given cell area of 50 cm^2. At larger cell sizes (200 cm^2) and at stack level, CFD analysis has been reported by a research group at Forschungszentrum Juelich using the porous volume method [32–34]. The CFD study was instrumental in illustrating that the flow field design was more dominating than the heating strategy in the final local current density distribution. It can be noted that for HT-PEFCs, serpentine flow fields have been selected in a significant number of works, thus highlighting its importance. Krastev et al. also carried out CFD study of a serpentine flow field to investigate electrical and thermal performance