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Superiority of a novel conic tubular PEM fuel cell over the conventional cylindrical one

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ABSTRACT

Polymer electrolyte membrane fuel cell (PEMFC) is one of the promising electricity generating technologies; however, it needs further improvements to be commercially viable. The design of a PEMFC plays a key role in its viability. This study proposes a novel conical tubular PEMFC and compares it with the conventional cylindrical tubular one through numerical simulation. The conversion of the cylindrical design into the conical one is done in such a way that the volume of each PEMFC component remains unchanged. The results illustrate the performance superiority of the conical design over the cylindrical one, and show that this superiority increases by increasing the conical angle and holds true for all settings of feeding conditions examined in this study. Moreover, the results indicate that among various feeding parameters, the relative humidity of the inlet reactants has greatest influence on the effectiveness of the proposed shape conversion, and the effectiveness is inversely proportional to the degree of humidification. In the current study, the superiority of the conical design over the cylindrical one in the maximum power is between 4.5% and 11.4% and in the average power is between 2.02% and 8.4%. The paper discusses in detail the reasoning for the mentioned observations.

Introduction

The consumption of fossil fuels is considered to be the major cause of environmental pollution, and the fossil fuel resources will be depleted in the coming decades. These problems necessitate paying special attention to the alternative sources of energy.

Polymer electrolyte membrane fuel cell (PEMFC) is one of the promising technologies due to its several beneficial characteristics such as high efficiency, high power density, low weight, quick startup, low operating temperature, low (or zero) emission of pollutants, and working in silence [1]. Moreover, the overall operation of a PEMFC is simple; that is, part of chemical energy released during the formation of water from its elements is converted to electricity.

However, PEMFC technology needs further improvement to be commercially viable. The design of a PEMFC plays a key role in its viability, and is often reduced to the design of its gas channels which highly affects the transfer of reactants to the reaction zones. As a result, various research works have focused on this topic. These works may be classified into three general categories as follows:

First group of works have focused on the influence of the path shape (e.g., parallel, serpentine, and inter-digitated) of the flow of reactants through a PEM stack on various parameters such as the rates of reactions, the distribution of reactants throughout the stack, the capability of water removal,

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Nomenclature

a_w	Water activity
C	Molar concentration, kmol m^{-3}
CL	Catalyst layer
c_p	Specific heat capacity, J $kg^{-1}k^{-1}$
C_w	Mass concentration of water, kg m^{-3}
D	Diffusion coefficient, m^2 s^{-1}
D_w	Water diffusivity, m^2 s^{-1}
F	Faraday constant, 96485 C mol^{-1}
GDL	Gas diffusion layer
GFC	Gas flow channel
I	Current, A
j	Transfer current density, A m^{-3}
k	Thermal conductivity, w $m^{-1}k^{-1}$
k_p	Permeability, m^2
M	Molecular weight, kg $kmol^{-1}$
$M_{m,dry}$	Equivalent weight of a dry membrane, kg $kmol^{-1}$
n_d	Electro-osmotic drag coefficient
P	Pressure, kPa
R	Universal gas constant, 8.314 kJ $kmol^{-1}K^{-1}$
RH	Relative humidity
S	Source term in governing equation
T	Temperature, K
U	Velocity, m s^{-1}
V	Voltage, V
X	Mole fraction
Y	Mass fraction
Greek letters	
α	Transfer coefficient
γ	Concentration dependence
ε	Porosity
η	Overpotential
λ	Water content
μ	Viscosity, kg $m^{-1}s^{-1}$
ξ	Specific active surface area, m^{-1}
ρ	Density, kg m^{-3}
$\rho_{m,dry}$	Density of dry membrane, kg m^{-3}
σ	Electrical conductivity, $\Omega^{-1}m^{-1}$
$\varnothing$	Phase potential, V
φ	Stoichiometry
Subscripts	
An	Anode
Ca	Cathode
I	Gas species
Mem	Electrolyte phase
Mix	Mixture
Oc	Open circuit
React	Reaction
Ref	Reference
Sat	Saturate
Sol	Solid phase
Superscripts	
Eff	Effective
Ref	Reference

and pressure drop [2–6]. Reviews of works of this type may be found in Refs. [7] and [8].

Second group of studies has investigated the influences of shape (e.g., rectangular, trapezoid, triangle and semicircle) and dimensions of gas flow channels cross sectional area on various performance criteria such as the distribution of temperature and reactants within the cell, pressure drop, and polarization curve [9–13]. Ref. [14] developed a two-dimensional, two-phase flow, non-isothermal, agglomerate model to study the distributions of liquid water and heat and CL effectiveness factors within the MEA and channels of a low temperature PEMFC. Results showed that low liquid water saturation is associated with large contact angle, low electrode porosity and platinum loading, and short and deep channel. Moreover, a novel channel design featured with multi-outlets and inlets along the channel was proposed to mitigate the effect of water flooding and improve the cell performance. Numerical investigations of Ref. [15] indicated that the size ratio of a PEMFC with a trapezoidal cross-sectional shape has a significant effect on the flow cross-over. Numerical comparison of PEMFCs with rectangular and trapezoidal channel shapes carried out by Ref. [16] showed that although the rectangular channel led to greater power, the trapezoidal channel resulted in more uniform distributions of reactants and current densities, and hence, it resulted in lower overpotential. Moreover, it was observed that the increase of shoulder width caused the ohmic loss to reduce, but it increased the concentration loss. The experimental investigations of Ref. [17] showed that the optimal channel size obtained when the pressure drop and generated power were considered simultaneously was different from that obtained when only generated power was taken into consideration. It was numerically shown by Ref. [18] that at high operating voltages (or low current densities), oxygen sufficiently reaches the reaction region, and therefore, channel design has negligible effect on the performance of a PEMFC. However, at low operating voltages (or high current densities), the performance of a PEMFC highly depends on the channel design, and smaller channel cross sectional area improves water removal, and consequently, the performance of the PEMFC. Ref. [19] adopted a combined optimization procedure, including a simplified conjugate-gradient method and a three-dimensional, two-phase, non-isothermal model, to optimize the flow field design of a serpentine PEMFC with five channels. Channel heights constituted the design variables. The obtained optimal design had three tapered channels and a final diverging channel, and achieved an 11.9% increment in the power density as compared to the basic case (i.e., a cell with straight channels). A similar work was carried out by the same authors [20], except that channel widths were also included in the set of design variables in addition to channel heights. The resulted optimal design had a tapered characteristic for channels 1, 3 and 4, and a diverging characteristic in height for channels 2 and 5. In this case, the superiority of the optimal design in the power density over the basic case was about 22.5%. Ref. [21] numerically investigated the influence of sub-rib convection on the performances of PEMFCs with single and triple serpentine flow fields. The results illustrated that for the single serpentine flow field in which sub-rib convection presents under all ribs, changing channel aspect ratio has