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A novel, state-of-the-art tubular architecture for polymer electrolyte membrane fuel cells: Performance enhancement, size and cost reduction

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ABSTRACT

Well-designed architectures of polymer electrolyte membrane fuel cells (PEMFCs) have recently proved the capability of improving the stack performance and reducing its size. This study introduces a novel tubular multi-channel architecture with exceptional capabilities for PEMFCs. This new design is studied through a well-validated three-dimensional non-isothermal model in Fluent. Comparing the polarization curves shows that the two introduced tubular designs are significantly more efficient than the conventional, flat-shape PEMFC having the same active area. In addition, the tubular cells are considerably smaller in size and require less bipolar plates per unit active area. For these reasons, the tubular shape is superior to the conventional, flat-shape design of PEMFCs.

The nesting tubular configuration shows more uniform distribution of oxygen, water, current density and temperature compared to both simple tubular and conventional flat architectures. More importantly, the nesting tubular design also produces significantly higher current density. As a result, the novel nesting tubular architecture enhances the PEMFC performance significantly while reducing its size and cost. The nesting tubular design can therefore be considered one of the best candidates for the next generation of PEMFCs.

1. Introduction

Despite being considered a main alternative to fossil fuel engines, polymer electrolyte membrane fuel cell (PEMFC) is still known as a fledgling industry. After several decades of fundamental research and development, PEMFC commercialization is still facing major challenges, mostly in terms of cost, power density and durability [1,2]. A great deal of investments and industrial efforts have been to date made towards materials characterization [3–6] and interfacial phenomena [7–9] without devoting any special attention to the stack architecture. The arrangement of the stack components and the impact of bipolar (flow field) plates on the reactant distribution over the catalyst layers play crucial roles in PEMFC's performance, cost and durability. Lack of any major breakthroughs in resolving such issues over the past decade [1,10,11] has bolded the limited capacity of the conventional, flat-shape architecture of PEMFCs. (i) The high cost of the bipolar plates required, (ii) the temperature and current distribution non-uniformity that intensifies degradation, (iii) the low access of reactants onto the catalyst layers and (iv) the relatively large volume of PEMFC stacks have long been considered among the main drawbacks of the conventional (flat-shape) PEMFCs. Many of these issues could be resolved by changing the architecture and design of PEMFCs stack.

Few novel configurations and architectures have been to date explored to improve conventional PEMFC power density, cost and durability. Through three studies, Pourmahmoud and Torkavannejad [12–14] showed that elliptical and circular channels have the capability of producing higher current density in comparison with the conventional PEMFCs. Moreover, they demonstrated that the cathode overpotential, known as the main cause of loss in PEMFCs, reduces. A similar study was conducted by Mohammadi-Ahmar et al. [15] for square, circular and triangular duct-shaped PEMFCs. They [15] showed through numerical simulations that circular and square architectures of PEMFCs enhance the current density and lead to more uniform reactant distributions over the catalysts but this is not the case with the triangular

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Nomenclature

a	water activity
A	area (m^2)
C	molar concentration ($mol\ m^{-3}$)
CCM	catalyst-coated membrane
Cell	fuel cell
D	diffusion coefficient ($m^2\ s^{-1}$)
F	faraday constant ($C\ mol^{-1}$)
GDL	gas diffusion layer
H	channel height (mm)
I	local current density ($A\ m^{-2}$)
i	local current density ($A\ m^{-2}$)
J	exchange current density ($A\ m^{-2}$)
K	permeability (m^{-2})
k	thermal conductivity ($W\ m^{-1}\ K^{-1}$)
L	channel length (mm)
M	molecular weight ($kg\ mol^{-1}$)
MEA	membrane electrode assembly
n_d	electro-osmotic drag coefficient
P	pressure (Pa or atm)
PEMFC	polymer electrolyte membrane fuel cell
R	universal gas constant ($J\ mol^{-1}\ K^{-1}$)
T	temperature (K)
u	velocity ($m\ s^{-1}$)
t	thickness (μm or m)
V	cell voltage (V)
V_{OC}	open-circuit voltage (V)
W	channel width (mm)
X	mole fraction
Y, y	mass fraction

Greek letters

$\varnothing$	potential (V)
α	transfer coefficient
β	a modified heat transfer coefficient accounting for both convective heat transfer and the specific surface area of the porous medium.
ζ	stoichiometric ratio
η	overpotential (V)
μ	viscosity ($kg\ m^{-1}\ s^{-1}$)
ρ	density ($kg\ m^{-3}$)
σ	ionic or electrical conductivity ($ohm^{-1}\ m^{-1}$)
ψ	humidity
ε	effective porosity

Subscripts and superscripts

a	anode
act	activation
ave	average
c	cathode
ch	channel
eff	effective value
GDL	gas diffusion layer
i	hydrogen at the anode side and oxygen at the cathode side
in	at the channel inlet
j	water
k	chemical species
land	land (rib) or shoulder
MEA	membrane electrolyte assembly
Mem	membrane
ref	reference value
sat	saturated
w	water

design. Khazaee and Ghazikhani [16,17] introduced the new architectures of annular and duct-shaped PEMFCs with connected channels. They showed that by increasing the number of connections between the gas diffusion layers and bipolar plates, the performance of the fuel cell enhances and the current density increases over the cathode catalyst layer. A ribbon-shape membrane electrode assembly (MEA) architecture was proposed by Walckzy and Sangra [18], which may provide more uniform current distribution and lower production cost. Tiss et al. [19] designed several blocks along the channel to force reactants into the gas diffusion layer. They observed an improvement to the output current density. Osanloo et al. [20] presented square duct-shaped PEMFCs with three different architectures of catalyst, membrane and gas diffusion layer. Their results showed higher current density and more uniform temperature and reactant distribution across the cell. Liu et al. [21] designed a novel fuel cell stack with coupled metal hydride containers which was found to be beneficial for the stack heat management. In their design, metal hydride containers, as cooling plates, were sandwiched between each pair of cells inside the stack so that the heat could be directly transferred to a metal hydride container of much larger surface-to-volume ratio than conventional separate containers.

According to the above-mentioned studies, innovative architectures and well-designed flow fields may enhance PEMFCs performance and reduce their cost. The final objective of using novel PEMFC architectures is to reach (i) considerably higher current and power densities; (ii) noticeably more uniform temperature, reactants and current density distributions; (iii) remarkably smaller cells and (iv) significantly less bipolar plates required.

In the present study, a novel, tubular nesting-shape architecture with specific capabilities is proposed for PEMFCs and compared with its simple tubular version and also with the conventional (classical), flat-shape design (the base model). By comparing the polarization curves through a numerical analysis, the present study investigates the possible advantages of the tubular architectures over the conventional, flat PEMFCs. It further discusses the capabilities that the tubular PEMFCs could offer in terms of current and power densities, the uniformity of current, temperature and reactant distributions inside the cell and any possible cost and/or size reduction. The simple and the novel nesting tubular architectures are analyzed to explore their possible potential for being one of the best candidates for the next generation of PEMFCs.

2. System description

The two tubular designs proposed for PEMFCs are shown in Fig. 1. In these simple and nesting tubular stacks, each MEA is in contact with two and four MEAs, respectively. In either design, each channel is connected to two different MEAs. This novel feature provides larger reaction area per unit volume and therefore, has the capability of enhancing the power density. The nesting tubular type is similar to the simple one but provides more channels with less cross-sectional areas per unit volume and in this aspect, it may be superior to its simpler version. The reactant gases are supplied to the cell from the inlet channels and exit it from the end side. Each cathode electrode is in contact with two anodes and