



Modeling and design of PEM fuel cell stack based on a flow network method

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HIGHLIGHTS

- A fuel cell stack model is established incorporating the cross flow effect.
- Pressure and mass distributions in the fuel cell stack are obtained.
- The optimal flow channel design is obtained.
- The optimal cooling channel design is obtained.

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ABSTRACT

Proton exchange membrane fuel cells are usually connected in series to form a fuel cell stack in order to satisfy the power demand of the practical applications. It is necessary to investigate the designs of the fuel cell stack to achieve the uniformity of reactant distributions and maximize the performance of the fuel cell stack. In this study, a fuel cell stack model is established based on the flow network method. The pressure and mass distributions of the reactant gas and coolant streams are determined by the flow network method incorporating the cross flow effect and the minor losses. The temperature distributions are also considered, and the individual cell performances in the fuel cell stack are obtained. The optimization of the fuel cell stack is also carried out after the stack model is validated by the experimental data. The flow channels are optimized in terms of the stack net power considering the pumping power losses and the cooling channels are optimized in terms of minimum power consumption for the same amount of cooling effect. Finally, the optimal designs for the fuel cell stack are obtained.

1. Introduction

Proton exchange membrane (PEM) fuel cell (PEMFC) converts the chemical energy of the fuel directly into electrical energy and is widely regarded as a clean and promising energy conversion device, with its environment-friendly characteristics of almost zero exhaust emission, low operating temperature and fast start-up features. Since the output power of a single PEMFC is limited, fuel cells are commonly connected in series to form a fuel cell stack in order to satisfy the power demand of the practical applications. In a fuel cell stack, reactants supplied from the stack manifolds flow through the fuel cells in multiple channels arranged in a complex flow network. The reactant flow and pressure distributions in each cell may vary from cell to cell and the heat and water management strategies for single PEM fuel cell are difficult to be implemented, which will cause the overall fuel cell stack performance degradation [1]. Therefore, it is necessary to optimize the fuel cell stack

design and operating parameters for better performance.

A considerable number of literatures exist for the modeling and simulation of the single fuel cell [2–12] and various types of methods are categorized and summarized in [13]. However, quite limited number of studies exist for the modeling and optimization of the PEM fuel cell stack. At the early stage, the lumped fuel cell stack model was utilized to analyze the thermal management of fuel cell [14,15]. This kind of fuel cell stack thermal models treated the whole stack as the control volume, they considered the heat exchange at the stack surfaces and the internal heating by the stack reactions or external heat sources, but were unable to predict the temperature distribution in each cell of the stack. Later, the layered fuel cell stack models were proposed which considered the cell unit and its components [16–18]. The benefit of the 1D layered model was that the temperature distribution in each cell was obtained, and the reaction heating and external heating or cooling could be applied to the cell unit, which provided more accurate

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Nomenclature

A_{cell}	active cell area (m^2)
A_{sec}	channel cross section area (m^2)
A_{heat}	heat transfer area (m^2)
C_f	wall friction coefficient
C_l	laminar wall friction coefficient
D_h	hydraulic diameter (m)
E	voltage (V)
E_{cell}	cell voltage (V)
E_{rev}	reversible cell voltage(V)
E_{th}	thermoneutral voltage(V)
F	Faraday constant ($96,485 \text{ C mol}^{-1}$)
h	heat transfer coefficient ($\text{W m}^{-2} \text{ K}^{-1}$)
H	heat transfer rate (W)
J	cell current density (A m^{-2})
K	permeability (m^2)
L	branch length (m)
$\dot{m}$	mass flow rate (kg s^{-1})
M	molecular weight (g mol^{-1})
n	exponent used to represent frictional/minor losses
$\dot{N}$	molar flow rate (mol s^{-1})
$\dot{N}_0$	initially assumed molar flow rate (mol s^{-1})
N_{branch}	number of segments in a loop (6)
N_{cell}	number of cells
N_{loop}	number of loops ($N_{\text{cell}}-1$)
$\dot{N}_r$	reactant consumption rate (mol s^{-1})
Nu	Nusselt number
P	pressure (Pa) or perimeter (m)
Pr	Prandtl number
$\dot{Q}, Q$	volume flow rate ($\text{m}^3 \text{ s}^{-1}$)
r	flow resistance coefficient
R	universal gas constant ($8.314 \text{ kJ kmol}^{-1} \text{ K}^{-1}$)
Re	Reynolds number
S	stoichiometry
T	temperature (K)
Y	molar fraction

Greek letters

α	thermal diffusivity ($\text{m}^2 \text{ s}^{-1}$)
Δ	difference

η	overpotential (V)
θ	flow direction convention (+1 for clockwise, -1 for counter clockwise)
κ	thermal conductivity ($\text{W m}^{-1} \text{ K}^{-1}$)
μ	viscosity (N s m^{-2})
ρ	density (kg m^{-3})
ν	kinematic viscosity ($\text{m}^2 \text{ s}^{-1}$)

Subscripts

air	air
an, anode	anode
bp	bipolar plate
branch	branch (control volume)
c	coolant/cooling channel
ca, cathode	cathode
cell	fuel cell
drag	dragged molecules
e	electrode backing
f	friction
GDL	gas diffusion layer
h	hydraulic diameter
H_2	hydrogen
H_2O	water
i	loop number
in, inlet	in/inlet value
j	branch number
l	laminar flow
logmean	log mean
loop	loop
m	minor loss/membrane
out/outlet	out/outlet value
O_2	oxygen
r	reacting
rev	reversible
sat	saturation
sec	cross section
stack	stack
th	thermo-neutral
0	initial/inlet value

temperature distribution than the lumped stack model. The layered fuel cell stack models were mainly used for the stack thermal management, but they were incapable of predicting the uneven reactant mass and pressure distribution in the fuel cell stack, and the mass and pressure were usually assumed uniform in the cells if they were considered in the layered stack model [18]. In order to obtain the information of mass and pressure distribution, proper discretization methods must be applied in the fuel cell stack modeling, usually based on the mass and energy conservation laws. Thirumalai and White [19] developed an isothermal performance model of a PEM fuel cell stack and they found that the cell voltage variation was caused by the unequal gas flow to the individual cells. Baschuk and Li [20] established a PEM fuel cell stack model based on a flow network approach, in which the pressure and mass flow rates were obtained and used as the operating condition inputs for a pre-established single fuel cell model [21]. They investigated the effect of the stack manifold size and the flow channel number on the cell performance variance, and found that the stack manifold hydraulic diameter should be large enough or the channel hydraulic diameter should be sufficiently small to maintain the uniform cell performance in the fuel cell stack. Karimi et al. [22] extended to incorporate the minor loss in the stack model caused by the U-turns of

the channel and the flow confluence/branching at the channel-manifold intersections. The minor loss was found to have considerable impact on the flow distribution and the double-inlet design of the stack manifold was suggested to increase the flow uniformity. Karimi and Li [23] numerically studied the performance of a fuel cell stack when the reformat gas was used as the anode reactant. It was shown that the effect of CO_2 dilution of the hydrogen dominated reformat gas had a minimal impact on the stack performance, however, the CO-poisoning effect had a very serious adverse impact on the stack performance. The CO was produced via the reverse water gas shift reaction in the anode feed stream and the CO-poisoning of the stack performance was shown mitigated effectively by introducing oxygen to the anode feed stream. In Park and Li [24], a non-isothermal stack model was developed which incorporated a heat transfer model for the temperature distribution throughout the stack. They simulated the heat transfer to the fuel, oxidant and coolant streams, respectively, studied the effect of temperature distribution on the stack performance, and predicated the fuel cell stack performance for various stack design and operating conditions.

The cross flow effect is significant in PEM fuel cell with the most widely used serpentine flow channel layout [25]. The cross flow is

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