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Constructal optimization for a single tubular solid oxide fuel cell

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HIGHLIGHTS

- Constructal optimization of a tubular solid oxide fuel cell is carried out.
- Maximum power output is taken as optimization objective.
- Optimal constructs of the tubular solid oxide fuel cell are obtained.
- Local power output decreases along the flow direction of the fuel and air.

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ABSTRACT

Based on constructal theory, the structure of a single tubular solid oxide fuel cell (TSOFC) is optimized in this paper. The maximum power output is chosen as the optimization objective. The optimal constructs of the TSOFC are obtained. The results show that the local power output $P_{E,j}$ and the local current density i_j decrease along the flow direction. For the fixed anode, cathode and electrolyte volume fractions, there exist optimal anode, cathode and electrolyte thicknesses as well as the corresponding optimal fuel cell lengths which lead to the maximum power outputs of the TSOFC, respectively. For the fixed inner radius of the solid parts, there exist an optimal cathode thickness and an optimal fuel cell length which lead to the double maximum power output (the power output after twice maximization) of the TSOFC. The power output of the TSOFC after constructal optimization is increased by 18.20% compared to that of the TSOFC with cathode thickness $t_c = 2200$ μm and fuel cell length $L = 1.5$ m. The performance of the TSOFC is evidently improved by adopting the optimal constructs obtained in this paper.

1. Introduction

Fuel cell is an important electrochemical device with a high efficiency, a friend effect on environment and a high reliability. It has a promising prospect of development. There are various fuel cells in engineering, and solid oxide fuel cell (SOFC) is one of the attractive fuel cells that many scholars have shown great interest in Refs. [1–19]. Ferguson et al. [9] investigated the performances of the planar, tubular and cylindrical SOFCs based on finite volume method. They concluded that the counter-flow design of the planar SOFC was better than the other discussed flow regimes, and further made a performance comparison between the planar SOFC and tubular solid oxide fuel cell (TSOFC). Campanari [10] and Campanari and Iora [11] developed a thermodynamic model of the TSOFC stack [10] and a finite volume TSOFC model [11] with internal reforming of the hydrocarbon gas as well as irreversible loss evaluation of the internal TSOFC. The results showed that it was important to adopt the appropriate kinetic model and parameters to evaluate the activation polarization and reforming reactions. Jia et al. [12] considered an electrochemical model of a TSOFC with radiation heat transfer inside tube, and concluded that the biggest irreversible loss among the losses considered is the ohmic loss. They also found that with the increase in the electrolyte thickness, the power output of the TSOFC decreased; with the increase in the mean pore radius of the electrode, the power output increased. Jia et al. [13] further discussed the effect of the combustion zone geometry on the performance of the TSOFC with steady and transient states, and the results showed that the performance about the overall temperature and response time of the TSOFC would become better with the increase in combustion zone length. Jiang et al. [14]

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Nomenclature

A	area, m^2
dx	length of each element, m
E_{act}	activation energy, J mol^{-1}
F	Faraday's constant, C mol^{-1}
H	enthalpy, J mol^{-1}
h	heat transfer coefficient, W m^{-2} K^{-1}
I	current, A
i	current density, A m^{-2}
i_L	limiting current density, A m^{-2}
i_0	exchange current density, A m^{-2}
k	thermal conductivity, W m^{-1} K^{-1}
L	length of the cell, m
n	number of the elemental volume
$\dot{n}$	molar flow rate, mol s^{-1}
P_E	total power output, W
p	Partial pressure
R	universal gas constant, J mol^{-1} K^{-1}
R_{eqv}	equivalent ohmic resistance, Ω
R_{int}	ohmic resistance of the interconnection, Ω
r	radius, m
T	temperature, K
t	thickness, μm
V_{act}	activation overpotential, V
V_{cell}	actual voltage of the cell, V
V_{conc}	concentration overpotential, V
V_N	nerst voltage, V
V_{ohm}	ohmic overpotential, V
V_T	total volume, m^3
x_{H_2}	molar faction for hydrogen

Greek symbols

γ	pre-exponential coefficient, A m^{-2}
ε	emissivity
θ	angle taken up by the interconnection, rad
ρ	resistivity, Ω m
σ	Stefan–Boltzmann constant
ϕ	volume fraction

Subscripts

a	anode
air	air
c	cathode
e	electrolyte
eqv	equivalent
fuel	fuel
H_2	hydrogen
H_2O	water
in	inlet
int	interconnection
j	elemental volume
m	maximum
mm	twice maximum
N_2	nitrogen
O_2	oxygen
oo	twice optimal
opt	optimal
ref	reference
1	pre-heated air
2	air injection tube
3	cathode gas or cathode gas channel
4	solid parts
5	anode gas or anode gas channel

Superscript

~	dimensionless

investigated the electrochemical and thermal performances of a one-dimensional TSOFC, and the results showed that the increasing of the cell diameter would lead to the increases in both power output and ohmic loss. Bhattacharyya and Rengaswamy [15] optimized the gravimetric and volumetric power densities of a TSOFC by using multi-objective method, and the results showed that these two power densities and electrical efficiency of the TSOFC could be improved in all operating conditions considered in the study. Moreover, some scholars also studied the hybrid system combining SOFC with heat engines [16–19] to further improve the energy utilization efficiency of the SOFC system.

The performance analyses and optimizations of the fuel cells mentioned above are carried out based on specified geometries of the fuel cells. Actually, the geometries of the fuel cells can be optimized based on constructal theory [20–32], and many scholars carried out constructal optimizations of the fuel cells [33–40] based on this theory. Vargas et al. [33–35] and Chen [36] optimized the internal and external structures of the proton exchange membrane fuel cells (PEMFCs) with steady and transient states respectively, and the net power outputs of the fuel cells could be improved by adopting the optimal constructs of the fuel cells. Ordonez et al. [37] optimized the internal structures, accounting for the cathode, electrolyte and anode layer thicknesses as well as the flow channels, of a single SOFC by taking power density as optimization objective, and pointed out that this optimization method could be extended to the large SOFC systems. Wen et al. [38–40] optimized the net power output of a single SOFC with composite electrode by varying geometrics and operating parameters of the SOFC. The results showed that the performance variation was so sharp within the study range; therefore, it was important to choose appropriate parameters in the designs of the SOFC systems. Lorenzini-Gutierrez et al. [41] introduced the tree-shaped flow channels into the constructal design of a PEMFC, and provided a better flow performance than those of the conventional ones. Lepage et al. [42] optimized the multi-channel reactor of a microbial fuel cell based on constructal theory, and the entropy generation of the microbial fuel cell was reduced.

In Refs. [11,13], the performance of the TSOFC was analyzed with specified fuel cell geometry, and the model in Refs. [11,13] will be re-considered by introducing constructal theory in this paper. The total volume of the TSOFC is specified, but the internal structure and length of the TSOFC are free to vary to search for the optimal performance of the TSOFC. The irreversible losses in terms of activation, concentration and ohmic resistance losses as well as radiation heat transfer inside TSOFC remain considered. The electric circuit will be greatly simplified by adopting the approximate method used in Ref. [15]. The power output of the TSOFC will be maximized, and the corresponding performance of the TSOFC will be evidently improved.

2. Single TSOFC model

Consider a single TSOFC model as shown in Fig. 1 [11,13]. The pre-heated air (temperature $T_{air,in}$ and molar flow rate $\dot{n}_{air,in}$) enters the air injection tube (tube temperature T_2) from its left side, flows out from the bottom of this tube (air temperature along the tube