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Performance improvement of a direct carbon solid oxide fuel cell through integrating an Otto heat engine

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ABSTRACT

A novel system consisting of an external heat source, a direct carbon solid oxide fuel cell (DC-SOFC), a regenerator and an air standard Otto cycle engine is proposed to improve the performance of the DC-SOFC. Considering the electrochemical/chemical reactions, ionic/electronic charge transport, mass/momentum transport and heat transfer, a 2D tubular DC-SOFC model shows that the overall heat released in the cell can be smaller than, equal to or larger than the heat required by the internal Boudouard reaction. Three different operating modes of the proposed system are identified, and accordingly, analytical expressions for the equivalent power output and efficiency of the proposed system are derived under different operating conditions. The modeling results show that the Otto heat engine can effectively recover the waste heat from the DC-SOFC for additional power production especially at large operating current density. Comprehensive parametric studies are conducted to investigate the effects of the different operating conditions of DC-SOFC on its performance and heat generation. The effects of compression ratio, internal irreversibility factor and power dissipation of the Otto heat engine on the system performance improvement are also studied.

1. Introduction

The increasing global attention on energy crisis drives worldwide research interest in clean and high efficiency energy conversion devices, such as solid oxide fuel cells (SOFCs). SOFCs are all solid-state devices working at a high temperature (e.g. 800 °C). A typical SOFC has a sandwiched structure with a dense electrolyte between a porous anode and a porous cathode [1–3]. Fuels (e.g. H_2) and oxidants (e.g. O_2) are supplied to the anode and cathode, respectively. Through electrochemical reactions, chemical energy in fuels and oxidants can be converted into electrical power directly with a high efficiency. As fuels and oxidants are separated by the dense electrolyte, the post-process of emission gases is relatively easy.

Apart from gas fuels like H_2 and CO, the utilization of solid carbons in SOFCs has received rising attention as these widely spreaded solid fuels have high volumetric energy density, which can easily be obtained at a low cost. There are two main methods for direct solid carbon utilization in the SOFCs. One is electrochemical oxidation of solid carbon that is in direct contact with the electrode catalyst (usually called as direct carbon fuel cell, DCFC) [1,2], aiming for a high thermodynamic efficiency. However, this method yields a low power density due to difficult transport of solid carbon and poor contact between the carbon particles and the electrochemical reaction sites (triple phase boundaries: TPBs). The other method is solid carbon indirect utilization through an agent (usually called as direct-carbon solid oxide fuel cell, DC-SOFC), which converts solid carbon into gas fuel such as CO for the electrochemical reaction at the TPBs [3,4]. Compared with the first method, the second method provides a much higher power density due to easy gas transport and good contact between gas fuel and the TPBs. With verifications of its mechanism [5,6], catalysts are developed to further improve the performance of DC-SOFCs [7–10]. Besides, the concept of CO and electrical power co-generation is proposed and analyzed. The results suggest that a much higher exergy efficiency can be achieved by the DC-SOFC than DCFC [11]. Different agents have also been compared to explore the application of DC-SOFC [12]. It is found that DC-SOFC with H_2O as gasification agent for H_2 and CO production could achieve higher performance than that with CO_2 agent due to fast gasification kinetics using H_2O agent and low activation loss associated

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Nomenclature

Abbreviation

CHP	combined heat and power
DC-SOFC	direct-carbon solid oxide fuel cell
LSM	strontium-doped lanthanum manganite
Otto	Otto heat engine
SCCM	standard cubic centime per minute
SOFC	solid oxide fuel cell
TPB	triple phase boundary
YSZ	Yttrium stabilized zirconium

Roman

b	power dissipation due to friction, W
B_0	permeability coefficient, m^2
c_{CO_2}	molar concentration of carbon dioxide, $mol{\cdot}m^{-3}$
C_P	C_P is constant-pressure heat capacity, $J\,K^{-1}$
C_V	C_V is constant-volume heat capacity, $J\,K^{-1}$
C_{V_1}	heat capacity of the gases in the compression stroke, $J\,K^{-1}$
C_{V_2}	heat capacity of the gases in the power strokes, $J\,K^{-1}$
	distance between carbon layer and anode, μm
D_m^{eff}	effective diffusivity of species m, $m^2\,s^{-1}$
E_{act}	activation energy, $J\,mol^{-1}$
E_{CO}	equilibrium potential for carbon monoxide oxidization, V
E_{CO}^0	standard equilibrium potential for carbon monoxide oxidization, V
E_{eq}	equilibrium Nernst potential, V
F	Faraday constant, 96,485 $C\,mol^{-1}$
F_f	friction force, N
i_o	exchange current density, $A\,m^{-2}$
I	electrical current, A
I_R	internal irreversibility factor
$K_1;K_2$	constant temperature rate in Eq. (18), $(s\,K^{-1})$
n	number of electrons transferred per electrochemical reaction
N_i	flux of mass transport, $kg\,m^{-3}\,s^{-1}$
p	(partial) pressure, Pa
P	power output, W
P_f	friction-related power loss, W
$P_{Otto,r}$	reversible power of the Otto heat engine, W
r	compression ratio
R	gas constant, 8.314 $J\,mol^{-1}\,K^{-1}$
R_{ce}	reaction rate of Boudouard reaction, $mol\,m^{-3}\,s^{-1}$
ΔS_{W1}	entropy change along the hot isothermal branch, $J\,K^{-1}$
ΔS_{W2}	entropy change along the cold isothermal compression branch, $J\,K^{-1}$
Δt_{12}	time spent in the power stroke, s
T	temperature, K
$T_{1\sim4}$	temperatures of the working substance at the state points 1, 2, 3 and 4
u	velocity field, $m^3{\cdot}s^{-1}$
V	volume fraction
V_1	working substance volume along the constant-volume cooling branch, m^3
V_2	working substance volumes along the constant-volume heating branch, m^3
$W_{Otto,r}$	reversible work of the Otto heat engine, W
x_2	piston position at minimum volume, m
y_k	molar fraction of component k

Greek letters

α	charge transfer coefficient
β_{H_2}	electrochemical kinetics parameter for H_2
γ	ratio of specific heats
ε	porosity
η	efficiency
η_{act}	activation polarization, V
η_{ohmic}	Ohmic polarization, V
κ	permeability, m^2
λ	thermal conductivity, $W\,m^{-1}\,K^{-1}$
μ	dynamic viscosity of fluid, Pa s
θ	friction coefficient, $J\,s\,m^{-2}$
ρ	fluid density, $kg\,m^{-3}$
σ	conductivity, S/m
τ	tortuosity
τ_t	period of the Otto cycle, s
$\varnothing$	potential, V

Subscripts

an	anode
ca	cathode
CO	carbon monoxide
CO_2	carbon dioxide
H_2	hydrogen
l	ionic phase
O_2	oxygen
r	reversible
s	electronic phase

Superscripts

0	parameter at equilibrium conditions
eff	effective
L	local

with H_2 electrochemical oxidation. To further understand the detailed chemical/physical process in the DC-SOFCs, mathematical models are developed [13–16]. Our recent mathematical model analyses [17] prove the existence of heat balance in DC-SOFC when it operates at a relative low current density. When the DC-SOFC operates at a high current density to provide a large power density, the heat generated from the irreversible electrochemical losses and enthalpy change exceeds the heat demand by Boudouard reaction. Therefore, the efficiency of DC-SOFCs can be further improved at a wide range of operating current density by utilizing the waste heat [18].

Various thermodynamic cycles including Carnot cycle [19], Stirling cycle [20], Ericsson cycle [21], Brayton cycle [22], Rankine cycle [23], Braysson cycle [24] and Kalina cycle [25] have been used for the conversion of heat into power. Compared with these cycles, Otto cycle has interesting perspectives as the rapid combustion process takes place at a constant volume, which indicates an excellent potential to integrate with other systems. By applying the air-standard analysis on Otto cycle, a number of modeling works have been conducted on air-standard Otto cycle heat engines [26–29] to illustrate the thermodynamic aspects of engine performance. Gumus et al. [30] compared the performance of a reversible Otto cycle based on its maximum power, maximum power density and maximum efficient power, where they conclude that the design parameters at maximum efficient power conditions lead to more efficient engines than that at the maximum power condition. Besides, the maximum efficient power criterion may have a significant power advantage compared with maximum power density criterion. By considering multiple irreversible losses, Zhao et al. [31,32] evaluated the performance of an irreversible Otto heat engine and determined the

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