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Optimization of molten carbonate fuel cell (MCFC) and homogeneous charge compression ignition (HCCI) engine hybrid system for distributed power generation☆

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ABSTRACT

In a previous study, a new hybrid system of molten carbonate fuel cell (MCFC) and homogeneous charge compression ignition (HCCI) engine was developed, where the HCCI engine replaces the catalytic burner and produces additional power by using the left-over heating values from the fuel cell stack. In the present study, to reduce the additional cost and footprint of the engine system in a hybrid configuration, the possibility of engine downsizing is investigated by using two strategies, i.e. the use of a turbocharger and the use of high geometric compression ratio for the engine design, both of which are to increase the density of the intake charge and thus the volumetric efficiency of the engine. Combining these two strategies, we suggest a new engine design with ~60% of displacement volume of the original engine. In addition, operating strategies are developed to run the new hybrid system under part load conditions. It is successfully demonstrated that the system can operate down to 65% of the power level of the design point, while the system efficiency remains almost unchanged near 63%.

1. Introduction

Recently, interest in renewable resources and energy conversion systems has increased due to environmental concerns and conventional fossil fuel depletions. Fuel cell technology is considered as a promising candidate for this category with its high efficiency and almost zero pollutant emission. Among various types of fuel cells, those operating at high temperatures (~600–800 °C) generally show higher efficiency than those at relatively lower temperatures [1]. There are two major types of high-temperature fuel cells, which are solid oxide fuel cell (SOFC) and MCFC. The former is still under active research and development stage, but the latter is already commercialized for distributed power generation purpose.

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Nomenclature

A_{seg}	area of each segment (cm^2)
CI	compression ignition
ΔF	change in molar flow rate ($mol\ h^{-1}$)
ΔG	gibbs free energy change ($J\ mol^{-1}$)
ΔH	apparent activation energy for resistance parameters ($J\ mol^{-1}$)
E_{rev}	maximum reversible potential (V)
f	faraday's constant (96487 C mol^{-1})
F	molar flow rate ($mol\ h^{-1}$)
H	frequency factor for resistance parameters ($J\ mol^{-1}$)
i	current (A)
j	current density ($A\ cm^{-2}$)
K_p	equilibrium constant
M	molar fraction
NO_x	oxides of nitrogen
ODEs	ordinary differential equations
P	partial pressure (bar)
Q	energy required (J)
R	universal gas constant ($J\ mol^{-1}\ K^{-1}$)
R_{and}	irreversible loss at anode ($\Omega\ cm^{-2}$)
R_{cat}	irreversible loss at cathode ($\Omega\ cm^{-2}$)
R_{int}	internal cell resistance ($\Omega\ cm^{-2}$)
R_{total}	total irreversible loss ($\Omega\ cm^{-2}$)
R	specific heat ratio
T	temperature (K)
V_{opn}	operating cell voltage (V)
W	work output (J)
X	conversion degree

Greek letter

η	loss

Subscripts

and	anode
and, i	species at anode
cat	cathode
cat, i	species at cathode
CO	carbon monoxide
CO_2	carbon dioxide
H_2	hydrogen molecule
H_2O	water
i	species
Nern	Nernst
X	gas
c	compressor
t	turbine
comb	combustion

Several studies have attempted to hybridize these high-temperature fuel cell systems with other power generating technologies, in order to achieve additional power and efficiency of the overall system. Especially, due to its operating characteristics of MCFC, there have been many efforts to build the hybrid system on it. First of all, hybrid system of MCFC coupled with gas turbine (GT) was studied by several researchers [2–7]. Lunghi et al. analyzed and optimized an MCFC and GT hybrid system, which was shown to achieve over 58% efficiency by parametric performance evaluation [2]. Roberts et al. performed a dynamic simulation of an MCFC and GT hybrid system, and in their analysis, the hybrid system efficiency was ~57% [3]. Ubertini et al. proposed an MCFC system combined with a steam injected GT. The overall system efficiency was 69% [4]. Liu et al. presented a hybrid system composed of a pressurized MCFC and a micro GT. They simulated the hybrid system at both design and off-design operations, and the system efficiency was ~58% [5]. Rashidi et al. developed an MCFC system with a turbo expander, which had the system efficiency of ~60% [6]. Orecchini et al. analyzed an MCFC and micro-turbine hybrid system by using an in-house MCFC model with a plate reformer, and micro turbine-compressor model. The electrical efficiency of their hybrid system was ~74% [7]. Secondly, organic Rankine cycle (ORC) was proposed as a bottoming cycle of the MCFC for waste heat recovery [8–10]. Angelino et al. studied an MCFC plant with ORCs using various working fluids. The system efficiency was ~60% [8]. Sanchez et al. introduced a hybrid system, which is composed of MCFC, GT, and ORC. They performed an optimization of the system, and the hybrid system efficiency was ~59% [9]. Recently, Vatani et al. analyzed the hybrid system of ORC and a direct internal reforming MCFC (DIR-MCFC), which showed an efficiency of ~60% [10]. Finally, a hybrid system of MCFC with Stirling engine was also suggested [11,12]. Sanchez et al. developed an MCFC-Stirling engine hybrid system, and compared it with MCFC-Rankine and MCFC-Brayton systems. The efficiency of the former was ~61%, which was higher than the efficiencies of the other systems [11]. Recently, Escalona et al. analyzed two hybrid systems, which were MCFC-Stirling system and MCFC-SCO_2 (supercritical carbon dioxide turbine) system. The MCFC-Stirling system efficiency was 56% and the MCFC-SCO_2 system efficiency was ~59% [12]. Although many hybrid systems were introduced, most researches were focused on large-scale power generation, except for MCFC-Stirling system.

Recently, we developed a new MCFC-HCCI engine hybrid system for sub-megawatts distributed power generation [13]. This new hybrid system was modeled by using the Mathworks Matlab and Cantera toolbox, and compared with the standalone counterpart. At comparable boundary conditions, the former demonstrated ~20% (relative) improvement in both power output and system efficiency, as compared to the latter, which proved itself to be a promising candidate for highly-efficient distributed power generation system in the near future. Fig. 1 shows a schematic of (a) standalone system using catalytic burner and (b) hybrid system using HCCI engine.[1]

In this study, we present the results on the feasibility of the hybrid system in a real-world application. There were three major issues discussed in our previous work [13]:

1. To downsize the HCCI engine in the hybrid system

[1] Turbocharger, shown in Fig. 1, was not included in our previous hybrid system.