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Thermodynamic evaluation and multi-objective optimization of molten carbonate fuel cell-supercritical CO_2 Brayton cycle hybrid system

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ABSTRACT

Fuel cell-heat engine hybrid system is a relatively new discipline which proposes to utilize the excess high-temperature heat of the fuel cell as the heat source for the heat engine. This paper is concerned with a thermodynamic analysis of a molten carbonate fuel cell-SCO_2 Brayton hybrid system to optimize its performance based on a list of criteria. Four objective functions are considered, including energy efficiency, power density, exergy destruction rate density and ecological function density, to study the influence of four main parameters, including compressor inlet temperature and turbine inlet temperature of the Brayton cycle, and interconnect plate area and current density of the fuel cell, on the performance of the hybrid cycle. The strong conflict between the objective functions necessitates a multi-objective optimization procedure and, therefore, three scenarios are proposed, each takes into account a combination of three of these objective functions. The multi-objective evolutionary method integrated with non-dominated sorting genetic algorithm is used to obtain Pareto optimal frontiers. Finally, three efficient decision-making tools including TOPSIS, LINMAP and Fuzzy are employed by means of which the best answers in each case scenario are selected.

Examining the Fuzzy method results for example, in the first scenario, which doesn't consider power density, ecological function density and exergy destruction rate density meet their optimum values, 1.314 and 0.3864 kW/m^2, respectively. However, energy efficiency falls by 10% compared to its maximum, which occurs in the third scenario (0.6676), where ecological function density isn't included, and power density drops by 25% compared to its own in the second scenario (2.2783 kW/m^2), where energy efficiency is not. This indicates the strong confliction between the objective functions and also the necessity of this kind of analysis. However, the first scenario would roughly provide the best condition for the system if one wanted all the objective functions to be optimum all together.

1. Introduction

Fuel cells (FCs) have been the main subject of many studies during the last decades stemming from an increasing worldwide concern on environmental pollution, global warming, and energy sources. In addition to their inherently clean, efficient, and reliable services, FCs are capable of being coupled with different thermal cycles providing more efficient options. Various types such as solid oxide fuel cell (SOFC), molten carbonate fuel cell (MCFC), proton exchange membrane fuel cell (PEMFC), phosphoric acid fuel cell (PAFC) and direct carbon fuel cell (DCFC) are examined and represented in the literature [1–5]. However, these systems can still be examined from different points of view. Thermodynamic evaluation and numerical investigation on thermal performance can be a perfect tool for identifying the ways of improving the efficiency of thermal systems [6–10]. Zhao et al. [1] developed a thermodynamic model to study an irreversible SOFC, using the theory of electrochemistry and non-equilibrium thermodynamics. Zhang et al. [3] analyzed MCFC form thermodynamic-electrochemical point of view and derived useful expressions for computing main parameters of the fuel cell, including cell voltage, power output, efficiency, and entropy production rate. They also used a multi-optimization method enabling to consider the energy efficiency and power output concurrently.

To further grow FCs' future market, different solutions have been

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Nomenclature

A	area (m^2)
C	heat capacity (W/K)
e	ecological function density (W/m^2)
E	ecological function (W)
En_{act}	activation energy (J/mol^2)
exd	exergy destruction rate density (W/m^2)
Exd	exergy destruction rate (W)
F	Faraday constant (C/mol)
g	molar Gibbs free energy (J/mol)
$\Delta\dot{G}$	change of Gibbs free energy rate (W)
h	molar enthalpy (J/mol)
Δh	molar enthalpy change (J/mol)
$-\Delta\dot{H}$	change of enthalpy rate (W)
j	current density (A/m^2)
k	ratio of specific heats
K	heat conductance ($W/m^2 \cdot K$)
n_e	number of electrons
p	pressure (atm)
p	power density (W/m^2)
P	power (W)
$\dot{Q}$	heat rate (W)
R	universal gas constant (J/mol·K)
T	temperature (K)
U	potential (V)
x	isentropic temperature

Subscripts

an	anode
B	Brayton
C	fuel cell
cat	cathode
CO_2	carbon dioxide
cp	compression
ex	expansion
h	hot side
H	hybrid
H_2	hydrogen
H_2O	water
i	ideal standard
l	cold side
max	maximum
o	environmental condition
O_2	oxygen
ohm	ohm overpotential
r	regenerator
rc	recuperator
rev	reversible
s	isentropic condition
SCO_2	supercritical carbon dioxide cycle
t	theoretical maximum potential

Greek letters

η	energy efficiency
ε	effectiveness

Abbreviations

C	compressor
DCFC	direct carbon fuel cell
FC	fuel cell
FTT	finite time thermodynamic
GA	genetic algorithm
GT	gas turbine
HE	heat exchanger
MCFC	molten carbonate fuel cell
MOEA	multi-objective evolutionary algorithm
MOO	multi-objective optimization
NSGA	non-dominated sorting genetic algorithm
PAFC	phosphoric acid fuel cell
PEMFC	proton exchange membrane fuel cell
Rec	recuperator
Reg	regenerator
SCO_2	super critical carbon dioxide
SOFC	solid oxide fuel cell
T	turbine

investigated. As one with the most promising results, hybridization of fuel cells has been advanced by which excessive heat rejected of high temperature is recovered in order to improve the energy efficiency. It has been shown that different configurations of fuel cell-heat engine hybrid systems are practicable [11–30]. SOFC and MCFC work at high temperature and, therefore, are more appropriate for these applications. Zhang et al. [16] developed a model taking into account multi-irreversibilities of a hybrid MCFC-heat engine system and their influence on the performance of the system. In a similar manner, the optimal performance of a hybrid system consisting of MCFC and gas turbine was discussed by determining the power output and efficiency expressions [18]. Chen et al. [21] studied an MCFC-Stirling engine hybrid system and showed the efficiency improvement of the hybrid system because of the coupling. They also investigated the performance dependency of the hybrid system to main operating conditions, including operating temperature, partial pressure of gases in anode and cathode and operating pressure. The upper and lower bounds of the objective functions were determined as well. In another study, Zhang et al. [26] developed a model describing the general characteristic of an MCFC-gas turbine hybrid system with direct internal reforming. In the proposed system, the auxiliary burner served as a high-temperature heat reservoirs of the Brayton cycle.

Among the different configurations, conventional Brayton cycle has been proved to be one of the most practical bottom-cycle. Since these systems are more compact compared with steam systems lower capital cost is required. In SCO_2 Brayton cycles, CO_2 above its critical point is applied as the working fluid. Due to thermodynamic conditions of the working fluid, there is significant decrease in compressor work, which results in higher efficiency of the cycle. Some of the studies conducted on hybrid MCFC-SCO_2 Brayton heat engines are represented in Refs. [31–35]. In Refs. [31,32], SCO_2 and air Brayton-MCFC hybrid systems are compared and it was observed that SCO_2 Brayton cycle-MCFC hybrid system is more favorable both in efficiency and output power. Mahmoudi and Ghavimi [34], conducted a study on MCFC-SCO_2 Brayton-organic Rankine cycle hybrid system and applied thermo-economic and multi objective optimization methods to analyze the system performance. Obtained results showed that exergy efficiency could be achieved up to 65.3% and product unit cost decreased to 0.039 cent (US/kWh). In another study, MCFC-SCO_2 Brayton hybrid system was compared with MCFC-organic Rankine cycle hybrid system [33]. Results indicated that by applying SCO_2 Brayton hybrid system as a bottoming cycle, compared with organic Rankine cycle, approximately 5% increase in energy efficiency was reachable. In Ref. [35], exergy analysis was conducted on MCFC-SCO_2 Brayton cycle. Result showed that overall energy and exergy efficiency of the system were 78% and 50%, respectively. In addition, it was found that exergy efficiency of reformer