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Research paper

Exergetic, economic, and environmental evaluations and multi-objective optimization of a combined molten carbonate fuel cell-gas turbine system

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ABSTRACT

The principal goal in the present work is to model a molten carbonate fuel cell-gas turbine (MCFC-GT) hybrid plant from energetic, exergetic, economic and environmental standpoints and to optimize the system through a multi-objective optimization scheme. Two conflicting objectives including exergetic efficiency and total cost rate of the system are introduced for multi-objective optimization. TOPSIS decision-making method is employed to determine the system final optimum design, leading to an overall exergetic efficiency of 51.7% and the total cost of 0.324 million USD per year. Moreover, a sensitivity analysis of the Pareto frontier to fuel unit cost and effective interest rate has been performed to investigate the variation of objective functions with economic parameters. Finally, a sensitivity analysis on the optimization results was performed for some of the key parameters, revealing the fact that operating pressure of the system has the highest impact on the exergetic efficiency compared to the other operating parameters.

1. Introduction

Fuel cell systems are an appropriate alternative to conventional power generation systems specifically in micro scale distributed systems due to their relatively high efficiency and lower environmental effects [1–4]. Molten carbonate fuel cells (MCFCs) are high-temperature fuel cells in which a molten carbonate salt mixture is employed as the electrolyte [5]. In order to allow an effective ion conduction and avoid rapid voltage degradation, their operating temperature should be between 600 °C and 700 °C, which is high enough to provide fast kinetics and eliminate the need for a noble metal catalysts [6]. The high operating temperature and pressure of the MCFCs also makes them highly suitable to use in combined heat and power applications (CHP) [7]. Moreover, the high operating temperature enables MCFCs to internally reform fuels such as natural gas or landfill gas [8]. One alternative approach for enhancing the efficiency of MCFC systems is to integrate fuel cells with other power generators such as gas turbines [9–12], turbo expanders [13], or micro-gas turbines [14]. Accordingly, molten carbonate fuel cell (MCFC)/gas turbine (GT) hybrid system has attracted a great attention due to its higher efficiency [15].

Some of the previous works have been specifically focused on the mathematical modeling of the MCFC [16] and MCFC stack with internal reforming [17], while many research activities were dedicated to the analysis of the hybrid MCFC systems. Leto et al. [11] modeled a hybrid system consisting of a MCFC coupled with a micro-turbine, and also performed a sensitivity analysis by varying main operating parameters. They demonstrated that this system could reach electrical and overall efficiencies up to 60% and 70% respectively. El-Emam and Dincer [18] conducted energetic and exergetic analyses of an MCFC-GT system and obtained overall energetic and exergetic efficiencies of 42.9% and 37.75%, respectively. In addition, Rashidi et al. [13] conducted a similar study on an MCFC-Gas turbine system and achieved an overall energetic efficiency of 57.4%, exergetic efficiency of 56.2%, bottoming cycle energetic efficiency of 24.7% and stack energetic efficiency of 43.4%. In another study, an MCFC operated at ambient pressure and

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Nomenclature

A	area (m^2)
c_f	fuel unit cost (USD MJ^{-1})
CRF	capital recovery factor
$\dot{C}_{env}$	social cost of air pollution (USD s^{-1})
$\dot{C}_{tot}$	total cost rate (USD s^{-1})
C_{cold}	heat capacity rate of cold flow
C_{hot}	heat capacity rate of hot flow
E	open circuit voltage (V)
e	specific exergy (kJ kg^{-1})
$\dot{E}$	exergy flow rate (kW)
$\bar{e}$	specific exergy (kJ $kmol^{-1}$)
F	Faraday constant (96,485C mol^{-1})
h	specific enthalpy (kJ kg^{-1})
$\bar{h}$	specific enthalpy (kJ $kmol^{-1}$)
I	current (A)
J	current density (A m^{-2})
i	interest rate (%)
K	equilibrium constant
LHV	low heating value (kJ kg^{-1})
$\dot{m}$	mass flow rate (kg s^{-1})
N	operational hours in a year
n	system lifetime (year)
$\dot{n}$	molar flow rate (kmol s^{-1})
P	pressure (bar)
$\dot{Q}$	the time rate of heat transfer, kW
R	resistance (Ω m^{-2})
$\bar{R}$	universal gas constant (kJ kmol K^{-1})
r	pressure ratio
s	specific entropy (kJ kg^{-1} K^{-1})
$\bar{s}$	specific entropy (kJ $kmol^{-1}$ K^{-1})
S/C	steam to carbon ratio
T	temperature (K)
TIT	turbine inlet temperature (K)
U_f	fuel utilization factor
V	voltage (V)
$\dot{W}$	mechanical work (kW)
x	molar fraction
Z	capital cost USD
$\dot{Z}$	capital cost rate (USD s^{-1})

Greek symbols

ε	effectiveness
η	efficiency
Φ	maintenance factor
Ψ	exergetic efficiency

Subscripts

an	anode
B	burner
cat	cathode
C	compressor
CC	combustion chamber
Ch	chemical
D	destruction
El	electrochemical
f	fuel
G	electric generator
Gen	generated
HE-1	heat exchanger
HRE	heat recovery exchanger
ir	irreversibility
M	mixer
ne	nernst
Ph	physical
R	reformer
RHE	recovery heat exchanger
tot	total
T	turbine
WGS	water gas shift

combined with a STIG cycle was examined and efficiencies up to 69% were obtained [19]. In another research, it was observed that an MCFC with 46.4% efficiency has the capability of being integrated with a steam generation power system in order to achieve an overall efficiency of nearly 70% [20]. Akkaya and Sahin [21] investigated the energetic performance of a combined system consisting of an SOFC and an ORC running with R-113. The results revealed that the efficiency of the SOFC-ORC system is 14–25% higher than the efficiency of single SOFC because of the waste heat recovery through ORC.

In order to perform a comprehensive assessment of a power generation unit, economic aspects of the system should also be taken into account. Monaco and Di Matteo [22] performed an economic analysis of a 2.5 kW MCFC unit employing the life cycle assessment. Hengeveld and Revankar [3] carried out an economic analysis on a combined heat and power molten carbonate fuel cell system. They demonstrated that, in the case of extremely high electrical energy cost and low natural gas cost, this system becomes economically reasonable, leading to a satisfying payback period of 10 years. Dicks and Siddle [23] investigated the commercial prospects of MCFCs in different countries and markets. They proposed that a range of 300–400 kW might be the best choice for initial market entry. Moreover, thermo-economic optimization of a MCFC hybrid system has been conducted by Verda and Nicolin [9]. In their study, the design which results in an efficiency of 0.46, leads to the minimum cost of electricity of 0.036 USD per kWh. Sciacovelli and Verda [10] performed multi objective optimization of a MCFC-Gas turbine plant and investigated the effect of considering uncertainties such as methane conversion in the steam reformer, landfill gas composition and ambient temperature on the achieved set of optimal solutions.

In the recent years, due to the increasing environmental concerns, the amount of emission produced by power generation plants has been considered as a crucial issue. A method for investigating the environmental impact of MCFC in its lifetime has been proposed by Monaco and Di Matteo [22]. Shirazi et al. [24] conducted thermal-economic-environmental analysis and multi-objective optimization of a solid oxide fuel cell-gas turbine hybrid system. CO, NO_x and CO_2 emission costs were taken into account in the total cost rate of the cycle and minimized in the optimization process.

Although many work has been carried out on the modeling and optimization of MCFC based hybrid plants, no through study on the optimization of such systems, considering thermal, economic and environmental viewpoints, has been performed. Motivated by this research gap, in the present study, a comprehensive thermodynamic model of a hybrid MCFC-GT plant is first developed, which evaluates the behavior of the system from energetic and exergetic standpoints. An economic model is developed in order to estimate the total cost of the system including the capital cost, operating