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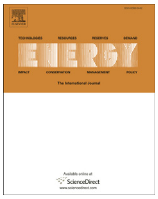

4E analysis and multi-objective optimization of an integrated MCFC (molten carbonate fuel cell) and ORC (organic Rankine cycle) system

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A B S T R A C T

This article proposes a novel hybrid system, integrating high temperature MCFC-GT (molten carbonate fuel cell-gas turbine) and ORC (organic Rankine cycle), which provides the possibility to achieve high electrical and exergetic efficiencies owing to the subsequent electrical power output in the bottoming cycle. After developing a mathematical model, comprehensive energetic, exergetic, economic and environmental evaluations (4E analysis) are performed and a multi-objective optimization method is utilized to find optimal solutions while considering the exergetic and economic objectives simultaneously. Two conflicting objectives including total exergetic efficiency and total cost rate of the system in multi-objective optimization are taken into account to build a set of Pareto optimal solutions. This optimum solution results in the exergetic efficiencies of 35.6%, 44.3%, and 54.9% for the fuel cell system, ORC cycle and the whole hybrid system respectively, while the total cost of the plant is 0.294 M€ per year. The study reveals that introducing the ORC bottoming cycle leads to about 5% improvement in the exergetic efficiency of the proposed plant. Furthermore, a sensitivity analysis is conducted to investigate the effect of variation in economic parameters, the fuel unit cost and interest rate, on the Pareto optimal solutions.

1. Introduction

The escalating fuel price, stricter environmental legislations, and continuous increase in energy consumption pose an urgent need for power generation technologies to operate in a more efficient, cost-effective and environment-friendly manner [1–3]. Furthermore, in the recent years, the distributed power generation has been identified as an economically viable option for small scale applications (up to several megawatts) and specifically for providing electrification to remote areas without access to public grid [4]. Within this context, fuel cells, especially MCFC (molten carbonate fuel cell) and SOFC (solid oxide fuel cell) have come into sight as competent alternatives to conventional power generation methods [5]. MCFC as a typical high-temperature fuel cell has attracted a great deal of attention due to its high efficiency, low emission of pollutants, and fuel flexibility based on its resistance to fuel impurities such as CO (carbon monoxide) [6]. Moreover, operation at elevated temperatures (600–700 °C) entails sufficient fast kinetics, allowing MCFC to use relatively inexpensive non-noble catalysts (Ni vs. Pt) [7]. In addition, one of the most encouraging characteristics of high temperature fuel cells, such as MCFC, is the high temperature of the exhaust gas, offering the possibility of cogeneration purposes or combination with other types of power generators such as gas turbine [8,9] and organic Rankine cycle (ORC) [10] to achieve a high efficiency and provide additional power.

Beside the experimental studies [5,11], many modeling and simulation studies of the MCFC have been going on to examine the electrochemical processes, the transport phenomena, and cell design [12–14]. A good overview over some steady-state models of MCFCs can be found in Koh et al. [15]. Likewise, in the development of integrated power systems based on fuel cell technologies, due to the obstacles upon experimental studies, numerical modeling plays a central role to explore the performance of the system in a wide range of operating parameters [16,17]. Lunghi et al. [18] studied an MCFC-GT hybrid system and performed a system optimization by varying the fuel cell size and the fuel utilization coefficient. Moreover, an MCFC operated at ambient pressure and combined with an

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Nomenclature

Acronyms

GA	genetic algorithm
LMTD	logarithmic mean temperature difference
MCFC	molten carbonate fuel cell
ORC	organic Rankine cycle
WGS	water gas shift

Symbols

A	area (m^2)
c_f	unit cost of fuel (€ MJ^{-1})
CRF	capital recovery factor
$\dot{C}_{env}$	social cost of air pollution (€ s^{-1})
$\dot{C}_{tot}$	total cost rate (€ s^{-1})
D	diameter (m)
E	open circuit voltage (V)
ex	exergy per unit mass (kJ kg^{-1})
$\dot{E}$	exergy flow rate (kW)
E_{act}	activation energy (kJ mol $^{-1}$)
$\bar{e}$	standard chemical exergy (kJ $kmol^{-1}$)
f	Darcy friction factor
F	Faraday constant (96,485C mol^{-1})
G	mass flux (kg m^{-2} s^{-1})
ΔG	Gibbs free energy (J mol^{-1})
h	specific enthalpy on a mass basis (kJ kg^{-1})
$\bar{h}$	specific enthalpy on a molar basis (kJ $kmol^{-1}$)
ΔH	enthalpy (kJ $kmol^{-1}$)
I	current (A)
i	interest rate (%)
j	current density (A m^{-2})
k	thermal conductivity (W/m K)
K	equilibrium constant
L	length (m)
LHV	lower heating value (kJ kg^{-1})
$\dot{m}$	mass flow rate (kg s^{-1})
M	molar mass (kg $kmol^{-1}$)
N	operational hours in a year
n	system lifetime (year)
$\dot{n}$	molar flow rate (kmol s^{-1})
p	pressure (Pa or bar)
Pr	Prandtl number
Nu	Nusselt number
q''	specific heat power (W m^{-2})
$\dot{Q}$	heat transfer rate (kW)
R	resistance (Ω)
R_u	universal gas constant (J mol^{-1} K^{-1})
Re	Reynolds number
r	pressure ratio
s	specific entropy on a mass basis (kJ kg^{-1} K^{-1})
$\bar{s}$	specific entropy on a molar basis (kJ $kmol^{-1}$ K^{-1})
S/C	steam to carbon ratio
T	temperature (K)
TIT	turbine inlet temperature (K)
U	overall heat transfer coefficient (W/m^2 K)
U_f	fuel utilization factor
V	voltage (V)
$\dot{W}$	power (kW)
x	molar fraction
Z	capital cost in €
$\dot{Z}$	capital cost rate (€ s^{-1})

Greek symbols

α	convective heat transfer coefficient (W m^{-2} K^{-1})
η	efficiency
Φ	maintenance factor
Ψ	exergetic efficiency
μ	viscosity (Pa s)
ρ	density (kg/m^3)
ε	effectiveness

Subscripts

an	anode
B	burner
cat	cathode
C	compressor
CC	combustion chamber
Ch	chemical
cond	condenser
D	destruction
el	electrical
env	environmental
evap	evaporator
ex	exergetic
exp	expander
f	fuel
g	electric generator
gen	generated
HE-1	heat exchanger
ir	internal
M	mixer
motor	electrical motor
ne	nernst
o:	outside
Ph	physical
pp	pinch point
preh	preheater
R	reformer
red	reduced
RHE	recovery heat exchanger
T	gas turbine
tot	total
wf	working fluid

STIG cycle was investigated by Ubertini and Lungh [19] and efficiencies up to 69% were obtained. Another study conducted by Varbanov et al. [20] revealed that coupling a steam generation power system with an MCFC plant leads to about 24% improvement in the overall thermal efficiency of the system.

ORC cycle can be employed downstream of the gas turbine to extract the remaining waste heat from the exhaust gases and provide even higher overall power output [21,22]. Akkaya and Sahin [23] studied the energetic performance of a combined system consisting of an SOFC and an ORC running with R-113. The results showed that the efficiency of the SOFC-ORC system is 14–25% higher than the efficiency of a single SOFC because of the waste heat recovery through ORC. Moreover, Al-Sulaiman et al. [24] suggested a tri-generation plant based on coupling an SOFC to an

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