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Process development and exergy cost sensitivity analysis of a hybrid molten carbonate fuel cell power plant and carbon dioxide capturing process

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HIGHLIGHTS

- A hybrid fuel cell system and carbon dioxide capturing process is developed.
- Cost of exergy destruction rate for the process components is calculated.
- The costs of exergy destruction and investment in most cases are endogenous.

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ABSTRACT

An integrated power plant with a net electrical power output of 3.71 × 10^5 kW is developed and investigated. The electrical efficiency of the process is found to be 60.1%. The process includes three main sub-systems: molten carbonate fuel cell system, heat recovery section and cryogenic carbon dioxide capturing process. Conventional and advanced exergoeconomic methods are used for analyzing the process. Advanced exergoeconomic analysis is a comprehensive evaluation tool which combines an exergetic approach with economic analysis procedures. With this method, investment and exergy destruction costs of the process components are divided into endogenous/exogenous and avoidable/unavoidable parts. Results of the conventional exergoeconomic analyses demonstrate that the combustion chamber has the largest exergy destruction rate (182 MW) and cost rate (13,100 $/h). Also, the total process cost rate can be decreased by reducing the cost rate of the fuel cell and improving the efficiency of the combustion chamber and heat recovery steam generator. Based on the total avoidable endogenous cost rate, the priority for modification is the heat recovery steam generator, a compressor and a turbine of the power plant, in rank order. A sensitivity analysis is done to investigate the exergoeconomic factor parameters through changing the effective parameter variations.

1. Introduction

High temperature fuel cells are good candidates for many integrated energy systems [1]. Molten carbonate fuel cells (MCFC) are used in large combined heat and power (CHP) and combined cooling and power (CCP) plants [2–4]. Exergoeconomic and environmental analyses are employed to analyze process performance. Both conventional and advanced exergy analyses place emphasis on reducing exergy destructions and obtaining enhanced thermodynamic performance [5–7], although many approaches do not take exergy destruction to be the main element in reducing capital and operating costs [8]. To overcome this issue, both thermodynamic and economic aspects must be considered in process performance analysis. The cost per unit exergy can be calculated using several approaches: exergy economic approach (EEA) [9], first exergoecocnomic approach (FEA) [10], exergetic cost theory (ECT)

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Nomenclature

A	Area (m^2)
A_{ir}	Frequency coefficient of cell internal resistance ($\Omega.cm^2$)
c	Unit exergy cost ($/kJ)
$\dot{C}$	Exergy cost rate ($/h)
e	Specific flow exergy (kJ/kmol)
$\dot{E}$	Exergy rate (kW)
E^0	Standard electro-motive force at the average cell temperature (V)
F	Faraday constant, 96,488.5 (°C/mol)
f	Exergoeconomic factor (%)
ΔH_{ir}	Activation energy (kJ/kmol)
ΔH_c	Activation energy of fuel gas (kJ/kmol)
ΔH_a	Activation energy of oxidant (kJ/kmol)
i	Current density (A/cm^2)
I	Local current density (A/cm^2)
$\dot{I}$	Irreversibility rate (kW)
i_{eff}	Average annual discount rate (cost of money) (%)
$\dot{m}$	Mass flow rate (kg/s)
n	Stoichiometric number of gas component
$\dot{n}$	Molar flow rate (kmol/s)
P	Pressure (bar)
P_j	Partial pressure of gas species j (bar)
PEC	Purchase equipment cost ($)
$\dot{Q}$	Heat transfer rate (kW)
r	Relative cost difference (%)
R	Characteristic gas constant (kJ/kg.K)
r_{FC}	Annual escalation rate for fuel cost (%)
r_{OMC}	Annual escalation rate for operating and maintenance cost (%)
S	Specific entropy (kJ/kmol.°C)
T	Temperature (°C)
T_e	Electrolyte temperature (°C)
$\dot{W}$	Electrical power (kW)
y	Exergy destruction ratio (–)
$\dot{Z}_k$	Total cost rate of *k*th component including capital investment and operating-maintenance cost($/h)
$\dot{Z}_i^{CI}$	Rate of capital investment of *k*th component ($/h)
$\dot{Z}_i^{OM}$	Rate of operating and maintenance cost of *k*th component ($/h)

Greek letters

η	Efficiency
ε	Exergy efficiency
τ	Annual operating hours (h)

Superscripts

AV	Avoidable
CH	Chemical
EN	Endogenous
EX	Exogenous

Superscripts

PH	Physical
TOT	Total
UN	Unavoidable

Subscripts

0	Index for first year of operation, reference thermodynamic condition
a	Air
c	Cold, consumed
D	Destruction
F	Fuel
h	Hot
i	Inlet
is	Isentropic
j	*j*th stream
k	*k*th component
L	Levelized
Min	Minimum
o	Outlet, other
p	Production
t	Total

Abbreviations

AC	Air cooler
BL	Book life
C	Compressor
CC	Combustion chamber, carrying charges
CI	Capital investment
CRF	Capital recovery factor
D	Drum
E	Heat exchanger
FC	Fuel cost
HE	Multi stream heat exchanger
HP	Horsepower
HRSG	Heat Recovery Steam Generation
Mix	Mixer
MCFC	Molten carbonate fuel cell
NG	Natural gas
OMC	Operating and maintenance cost
P	Pump
ROI	Return on investment
SOFC	Solid oxide fuel cell
T	Turbine
TCR	Total capital recovery
TRR	Total revenue requirement
V	Expansion valve

[11], engineering functional analysis (EFA) [12] and specific exergy costing (SPECO) [13]. Economic analysis can be combined with exergy analysis in exergoeconomic analysis and used to determine costs. This method can be implemented as a useful method for the comparison of processes [14], and several exergoeconomic methods have been developed. Among these, Kim et al. [15] presented a method consisting of exergy and economic analysis, based on a general cost balance equation. Exergoeconomic analyses of separate and integrated fuel cell processes have been reported [16,17]. For example, the performance of a CHP-SOFC system was analyzed for vehicular applications [17]. Raising the fuel cell output power from 35 to 70 kW was seen to increase the process exergy efficiency to almost 50%. Also, the exergy destruction of the fuel cell decreases by 13% when the current density is increased to about 30%. Exergy and exergoeconomic analyses have been applied numerous times for analyzing fuel cell performance [16,18–22]. For instance, an exergoeconomic analysis of a PEM fuel cell engine system for transportation applications found that the main contribution to the overall cost is made by the fuel cell stack which has the highest irreversibility of all process components [16]. The