Energy Conversion and Management 165 (2018) 291–303

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

# Investigation of a combined molten carbonate fuel cell, gas turbine and Stirling engine combined cooling heating and power (CCHP) process by exergy cost sensitivity analysis

Hojat Ansarinasab[a,c], Mehdi Mehrpooya[b,c,*]

[a] Faculty of Energy Systems Engineering, Petroleum University of Technology (PUT), Iran
[b] Renewable Energies and Environment Department, Faculty of New Sciences and Technologies, University of Tehran, Tehran, Iran
[c] Hydrogen and Fuel Cell Laboratory, Faculty of New Sciences and Technologies, University of Tehran, Tehran, Iran

ARTICLE INFO

*Keywords:*
Molten carbonate
Fuel cell
Stirling engine
Advanced exergoeconomic
Refrigeration

ABSTRACT

An integrated combined cooling, heating and power process is investigated and analyzed by advanced exergy cost analysis method. In this process molten carbonate fuel cell, gas turbine and Stirling engine are used for providing the required power (6482 kW). A double effect $H_2O$-Li/Br absorption refrigeration cycle supplies 980 kW cooling. Fuel cell exhaust heat is used to drive Stirling engine and absorption chiller. Also, gas turbine exhaust heat is used to produce steam for heating (2136.6 kW). The main result extracted from the endogenous and exogenous parts shows that cost interactions between the equipment in this hybrid system is not strong. Heat exchangers investment cost and exergy destruction cost are avoidable and unavoidable respectively, while opposite behavior is exhibited by the compressors. From avoidable exergy destruction cost point of view, compressor C-1 and from avoidable investment cost point of view, heat exchangers have high improvement potential. Also effects of key parameters on the exergoeconomic factor and exergy destruction cost rate are studied through the sensitivity analysis. Finally, three strategies are recommended for removing the inefficient costs and improving the system performance.

## 1. Introduction

Combined cooling heating and power (CCHP) power systems are considered as hybrid energy systems which their overall energy efficiencies is considerable [1]. Molten carbonate fuel cell (MCFC) and solid oxide fuel cell (SOFC) are two kinds of high temperature fuel cells which can be integrated with various systems like gas turbine (GT) [2], chemical looping processes [3], absorption refrigeration systems (ARS) [4] and Stirling engine (SE) [5] in order to increase overall energy efficiency of the system.

Stirling engine take advantage of external heat-source (e.g. fossil fuels and renewable energies). The working gas in these engines, operates on a closed regenerative thermodynamic cycle, with cyclic compression and expansion of the working gas at different temperature levels [6]. Authors interested in Stirling engine due to their good performance, high overall efficiency, low pollution emission levels and fuel flexibility [7].

Two new combined systems incorporating a fuel cell and a Stirling engine or a gas turbine were proposed [8]. The results show that the energy efficiency of the hybrid system which is integrated with Stirling engine is higher than other combined systems which is integrated with gas turbine. A hybrid system integrating a solid oxide fuel cell power cycle with a Stirling engine was developed [9]. The results present that energy efficiency of this type of plant is equal to 51% with 5 kW power output. A combined system containing SOFC, solar parabolic dish, double effect LiBr-$H_2O$ absorption chiller system and organic Rankine cycle is developed and analyzed [10]. The obtained results reveal that, electrical efficiency of the SOFC, combined system and overall thermal efficiency of the system are about 41.5%, 48.7% and 79.5%; respectively. A cogeneration system integrating a fuel cell with a Stirling engine in order to supply simultaneous heating and power [11]. The results show that the energy efficiency of this cogeneration system is almost 60%. Cost of the plant (2060 $/kW) was calculated through a simple economic analysis. An energy analysis is performed on a gasification system combined with a hybrid SOFC-Stirling cycle [12]. The results indicate that energy efficiency of the process is 42%. Also, the author carried out a thermodynamic and thermoeconomic analysis for this system [13].

Absorption refrigeration systems (ARS) can work with heat duty without any electrical power so they are preferred to vapor compression

* Corresponding author at: Renewable Energies and Environment Department, Faculty of New Sciences and Technologies, University of Tehran, Tehran, Iran.
*E-mail address:* mehrpooya@ut.ac.ir (M. Mehrpooya).

https://doi.org/10.1016/j.enconman.2018.03.067
Received 21 January 2018; Received in revised form 3 March 2018; Accepted 22 March 2018
0196-8904/ 

**Nomenclature**

| | |
|---|---|
| c | unit exergy cost ($ $GJ^{-1}$) |
| C | coulomb |
| $\dot{C}$ | exergy cost rate ($ $hr^{-1}$) |
| e | specific flow exergy (kJ kg $mole^{-1}$) |
| E | ideal voltage of the cell (V) |
| $\dot{E}$ | exergy rate (kW) |
| f | exergoeconomic factor (%) |
| F | faraday constant (C $mole^{-1}$) |
| G | gibbs free energy (kW) |
| H | enthalpy (kJ) |
| I | irreversibility (kW) |
| j | current density (mA $cm^{-2}$) |
| K | specific heat ratio |
| $\dot{m}$ | flow rate (kg $s^{-1}$) |
| P | pressure (bar) |
| Q | heat transfer rate (kW) |
| r | relative cost difference (%) |
| R | universal gas constant (J $mol^{-1}$ $K^{-1}$) |
| S | entropy (kJ °$C^{-1}$) |
| T | temperature (°$C^{-1}$) |
| V | real voltage of the cell (V) |
| $\dot{W}$ | power (kW) |
| x | mole fraction |
| y | exergy destruction ratio |
| $\dot{Z}$ | investment cost flow rate ($ $hr^{-1}$) |

*Greek letters*

| | |
|---|---|
| ε | exergy efficiency |
| Δ | gradient |
| τ | annual operating hours (h) |
| η | efficiency |

*Superscripts*

| | |
|---|---|
| AV | avoidable |
| EN | endogenous |
| EX | exogenous |
| TOT | total |
| UN | unavoidable |

*Subscripts*

| | |
|---|---|
| c | cold |
| ch | chemical |
| D | destruction |
| F | fuel |
| h | hot |
| i | inlet |
| k | *k*th component |
| o | outlet |
| P | production |
| ph | physical |

*Abbreviations*

| | |
|---|---|
| AC | alternative current |
| ARS | absorption refrigeration system |
| C | compressor |
| CC | combustion chamber |
| CCHP | combined cooling heating and power |
| CH | chiller |
| DC | direct current |
| E | heat exchanger |
| EOS | equation of states |
| HE | multi stream heat exchanger |
| is | isentropic |
| LNG | liquefied natural gas |
| LHV | lower heating value |
| MCFC | molten carbonate fuel cell |
| Mech | mechanical |
| Mix | mixer |
| NG | natural gas |
| NGL | natural gas liquid |
| ORC | organic rankine cycle |
| P | pump |
| RE | reformer |
| SOFC | solid oxide fuel cell |
| ST | stirling |
| T | turbine |
| Thermo | thermodynamically |

refrigeration cycles when the required heat duty would be available. Water-ammonia ARS is used for subzero refrigeration and water-Li-Br ARS is used for above zero refrigeration [14]. In CCHP systems, absorption refrigeration systems are used with exhaust heat from the gas turbine or fuel cell systems. A hybrid CCHP plant which uses MCFC and ammonia water ARS is introduced and analyzed [15]. In this study electrical efficiency of the process and refrigeration temperature are gained 58% (LHV) and −30 °C respectively. A hybrid SOFC fuel cell power plant which provides the required power for natural gas liquefaction is design and analyzed [16]. In this study an ammonia water ARS is used for supplying the required refrigeration in the precooling section of the liquefaction system. Integration of MCFC with absorption refrigeration system (ARS) is studied and analyzed [17]. In this study exhaust heat from the MCFC is used in ARS generator. The overall energy efficiency of this CCHP system is about 71%. A hybrid CCHP system which uses a $H_2O$-Li/Br absorption refrigeration cycle to provide the required refrigeration is studied [18].

Exergy and advanced exergy analysis methods are used to provide the data required for evaluating design and performance of the hybrid energy systems from thermodynamics point of view [19]. A hybrid CHP system incorporating MCFC, gas turbine and $CO_2$ capturing process is investigated and analyzed by exergy and advanced exergy analysis methods [20]. The results indicate that the lowest exergy efficiency is related to the fuel cell system. A large scale two stage compression gas turbine CHP system is analyzed by the exergy method [21]. The results show that overall exergy efficiency is 69%. An exergy-based method is performed on a new combined gas turbine, MCFC fuel cell and organic Rankine power cycle [22]. An exergy efficiency of 59.4% was achieved according to the exergy analysis. Energy and exergy analysis is carried out on a CCHP system which is uses SOFC, water-ammonia ARS and Rankine steam cycle [1]. A cogeneration system based on a methane-fed solid oxide fuel cell integrated with a Stirling engine is analyzed from the viewpoints of energy and exergy [23]. Energy efficiency of the combined system is found to be 76.32%. A hybrid trigeneration fuel cell power plant is introduced and analyzed. The results indicate that overall thermal efficiency can reach to about 71% [24].

Exergoeconomic and advanced exergoeconomic analysis methods merge the exergy concept and economic analysis parameters. So results of evaluation by these methods give valuable information about the process components role on the process performance [25–27]. An integrated natural gas liquids and liquefied natural gas process is analyzed by exergoeconomic method [28]. A hybrid MCFC-GT power plant