Energy Conversion and Management 87 (2014) 318–327

Contents lists available at ScienceDirect

Energy Conversion and Management

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

# Energy and exergy assessments of a novel trigeneration system based on a solid oxide fuel cell

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ARTICLE INFO

*Article history:*
Received 24 May 2014
Accepted 2 July 2014
Available online 30 July 2014

*Keywords:*
Solid oxide fuel cell
Trigeneration
Current density
Efficiency
Exergy
Energy
Exergy destruction

ABSTRACT

Energy and exergy assessments are reported of a novel trigeneration system based on a solid oxide fuel cell (SOFC), for steady-state operation and using a zero-dimensional approach. The trigeneration system also includes a generator-absorber heat exchanger for cooling and a heat exchanger for the heating process. The influences of two significant SOFC parameters (current density and inlet flow temperature) on several variables are investigated. The results show that the energy efficiency is a minimum of 33% higher when using the trigeneration system compared with the SOFC power cycle. In addition, the maximum energy efficiencies are found to be 79% for the trigeneration system, 69% for the heating cogeneration, 58% for cooling cogeneration and 46% for electricity production. Moreover, the highest trigeneration exergy efficiency is almost 47% under the given conditions. It is also shown that, as SOFC current density increases, the exergy efficiencies decrease for the power cycle, cooling cogeneration, heating cogeneration and trigeneration. As current density increases, the trigeneration energy and exergy efficiencies decrease, and an optimal current density is observed to exist at which the net electrical power is a maximum. As SOFC inlet flow temperature increases, the trigeneration energy and exergy efficiencies and net electrical power increase to a peak and then decrease. The main exergy destructions occur in the air heat exchanger, the SOFC and the afterburner.

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## 1. Introduction

Accessibility of energy resources and global warming are two important long-term problems. Global energy demand has steadily risen over time, notwithstanding the limited availability of non-renewable fossil fuels. As a consequence, more efficient and clean energy systems are being sought. The energy efficiency of conventional power plants based on single prime mover is usually less than 40%, with most of the energy loss associated with waste heat. Combining cooling and heating subsystems in a conventional plant can increase the system efficiency considerably, and energy efficiencies can reach 80% through trigeneration [1,2], the simultaneous production of cooling, heating and electricity, often from one energy source. Trigeneration, also referred to as a combined cooling, heating and power (CCHP), offers a number of potential benefits:

- Increased efficiency.
- Reduced fuel and energy costs.
- Significantly reduced greenhouse gas emissions.
- Shortened transmission lines.
- Fewer distribution units.
- Increased power supply reliability.

The primary driver is an important part of a trigeneration system, making its selection important. The main primary drivers are gas turbines, steam turbines, external combustion engines, internal combustion engines, micro-turbines, and fuel cells. Among these, trigeneration based on fuel cells often achieves higher energy efficiency, in part because the fuel cell avoids Carnot efficiency limitations.

The solid oxide fuel cell (SOFC) is considered an important emerging technology. It can produce electricity directly from a fuel, such as methane, and an oxidant, such as air. It operates at high temperatures and generates much waste heat, so it is commonly coupled with a gas turbine (GT) or an organic Rankine cycle (ORC) as a bottom cycle to improve the overall efficiency by

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http://dx.doi.org/10.1016/j.enconman.2014.07.014
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**Nomenclature**

| | |
|---|---|
| $a$ | activity factor of species in electrochemical reaction |
| $A_a$ | active surface area, $m^2$ |
| $D_{aeff}$ | effective gaseous diffusivity through anode, $m^2/s$ |
| $D_{ceff}$ | effective gaseous diffusivity through cathode, $m^2/s$ |
| $\overline{ex}_i^{ch,0}$ | standard chemical exergy of species, kJ/mol |
| $\dot{E}x$ | exergy rate, kW |
| $\dot{E}x^{ch}$ | rate of chemical exergy, kW |
| $\dot{E}x^{ph}$ | rate of physical exergy, kW |
| $F$ | Faraday constant, C/mol |
| $\Delta\bar{g}^o$ | change in molar Gibbs free energy, J/mol |
| GAX | generator absorber heat exchanger |
| $\bar{h}$ | molar enthalpy, J/mol |
| $I$ | current, A |
| $\dot{I}$ | exergy destruction rate, kW |
| $j$ | current density, $A/m^2$ |
| $j_{as}$ | anode-limiting current density, $A/m^2$ |
| $j_{cs}$ | cathode-limiting current density, $A/m^2$ |
| $j_{oa}$ | exchange current density of anode, $A/m^2$ |
| $j_{oc}$ | exchange current density of cathode, $A/m^2$ |
| $K$ | equilibrium constant of waste gas shift reaction |
| $L$ | thickness of SOFC layer, m |
| LHV | lower heating value, kJ/mol |
| $\dot{n}$ | molar flow rate, mol/s |
| $N_{FC}$ | total number of fuel cells |
| $\dot{Q}$ | heat rate, kW |
| $\bar{R}$ | universal gas constant, J/mol K |
| $R_{contact}$ | contact resistivity, $\Omega\,m^2$ |
| $r_{el,h}$ | electrical to heating ratio |
| $r_{el,c}$ | electrical to cooling ratio |
| $\bar{s}$ | molar entropy, J/mol K |
| $T$ | temperature, K |
| $U_f$ | fuel utilization ratio |
| $U_0$ | air utilization ratio |
| $V$ | voltage, V |
| $\dot{W}$ | power, kW |
| $\dot{W}_{FC,stack}$ | power output of fuel cell |
| $x_r$ | extent of steam reforming reaction for methane, mol/s |
| $y_i$ | molar concentration |
| $y_r$ | extent of water gas shift reaction, mol/s |
| $z_r$ | extent of electrochemical reaction, mol/s |

*Greek letters*

| | |
|---|---|
| $\eta$ | energy efficiency |
| $\psi$ | exergy efficiency |
| $\rho$ | electrical resistivity of cell components |

*Subscripts*

| | |
|---|---|
| 0 | atmospheric condition |
| a | anode |
| abs | absorber |
| ac | AC current, air compressor |
| act | activation |
| AHE | air heat exchanger |
| c | cathode |
| cog,c | cooling cogeneration |
| cog,h | heating cogeneration |
| conc | concentration |
| cond | condenser |
| cv | control volume |
| des | desorber |
| $e$ | electrolyte, exit |
| el | electrical power |
| evap | evaporator |
| fc | fuel compressor |
| FC | fuel cell |
| FHE | fuel heat exchanger |
| h | heating |
| HR | heat recovery |
| in | inlet |
| int | interconnect |
| inv | DC to AC inverter |
| ohm | ohmic |
| N | Nernst |
| tri | trigeneration |
| WHE | water heat exchanger |
| wp | water pump |
| – | molar |
| · | rate |
| 0 | standard pressure |
| ch | chemical |
| ph | physical |

recovering SOFC waste heat. Many researchers have studied the performance of SOFC-GT hybrid power plants [3–16], integrated SOFC-ORC power plants [17,18] and combined SOFC-Stirling hybrid plants [19]. Few analyses, however, have been reported of trigeneration power plants based on an SOFC. Some of the more significant of these are now described.

Weber et al. [20] conducted detailed $CO_2$ emission and cost analyses of a trigeneration system based on a SOFC primary mover in an office building, and demonstrated that the system reduced $CO_2$ emissions by 30% at a cost increase of 70% compared with a conventional system.

A trigeneration plant driven by a SOFC and a gas turbine was studied by Burner et al. [21]. The plant included half-, single- and double-effect chillers, a heat pump, an additional gas boiler, a heat recovery boiler, a compression chiller and cooling system. They considered the potential of combining a heat pump into the trigeneration system. The study considered energy and exergy efficiencies and concentrated on costs and $CO_2$ emissions, and demonstrated that the SOFC-GT system is attractive economically and environmentally. The study utilized multi-objective optimization based on a multi-criteria evolutionary algorithm, and incorporated the following optimization objectives: annual total cost of trigeneration and annual $CO_2$ emission rates.

Liu et al. [22] proposed a trigeneration plant by combining an internal-reforming solid oxide fuel cell (IRSOFC) with a zeolite/water adsorption chiller, and analyzed numerically the performance of the system under various operating conditions and parameters.

Yu et al. [23] analyzed a total energy system incorporating a SOFC and an absorption chiller driven by exhaust gas to provide electricity, cooling and/or heating simultaneously. They found that, as fuel utilization coefficient varies, both the electrical efficiency and total efficiency of the system achieved maximum values.

Al-Sulaiman et al. [24] carried out an energy analysis of a trigeneration system based on a SOFC and an ORC. The system also consisted of a heating process and a single-effect absorption chiller. The analysis demonstrated that, compared to only a power plant, trigeneration increases the efficiency by at least 22%. They also found that the exergy efficiency increased by 3–25% when trigeneration was applied [25].

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