Desalination 334 (2014) 46–59

Contents lists available at ScienceDirect

Desalination

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

Exergetic, economic and environmental analyses and multi-objective optimization of an SOFC-gas turbine hybrid cycle coupled with an MSF desalination system

Behzad Najafi [a], Ali Shirazi [b,*], Mehdi Aminyavari [c], Fabio Rinaldi [a], Robert A. Taylor [b]

[a] Dipartimento di Energia, Politecnico di Milano, Via Lambruschini 4, 20156 Milano, Italy
[b] School of Mechanical and Manufacturing Engineering, The University of New South Wales (UNSW), Kensington, New South Wales 2052, Australia
[c] Scuola di Ingegneria Industriale, Campus di Piacenza, Politecnico di Milano, Via Scalabrini, 76, 29100 Piacenza, Italy

HIGHLIGHTS

- Exergetic, economic and environmental analyses were performed on SOFC–GT–MSF system.
- Exergy efficiency and total cost rate were considered as the conflicting objectives.
- Total cost rate included capital, maintenance, operational and emissions costs.
- Multi-objective optimization was applied to obtain a set of optimal solutions.
- The effect of variations in fuel unit cost on system design parameters was studied.

ARTICLE INFO

Article history:
Received 26 September 2013
Received in revised form 28 November 2013
Accepted 30 November 2013
Available online 22 December 2013

Keywords:
Solid oxide fuel cell
Gas turbine
Multi stage flash distillation
Exergy
Environmental
Multi-objective optimization

ABSTRACT

The present study presents thermodynamic, economic and environmental (emissions cost) modeling of a solid oxide fuel cell–gas turbine (SOFC–GT) hybrid system integrated with a multi stage flash (MSF) desalination unit. A heuristic optimization method, namely, multi-objective genetic algorithm (MOGA) is employed afterwards to obtain the optimal design parameters of the plant. The exergetic efficiency and the total cost rate of the system are considered as the objective functions of the optimization procedure; where, the total cost rate of the system (including the cost rate of environmental impact) is minimized while the exergetic efficiency is maximized. Applying the optimization method, a set of optimal solutions is achieved and the final selected optimal design leads to an exergetic efficiency of 46.7%, and a total cost of 3.76 million USD/year. The payback time of the selected design is also determined to be about 9 years. Although the determined value for the payback period seems to be relatively high for the proposed plant (due to the high capital cost of the SOFC system), this integrated technology is expected to be promising in the near future as the capital costs of SOFCs are decreasing and their operational lifetimes are increasing.

1. Introduction

According to the U.S. energy information administration (EIA), the electrical energy demand is expected to rise by 22% from current levels by 2035 [1]. If this growth is met by conventional technology, it could create negative environmental ramifications. At the same time, increasing demand for rapidly diminishing fresh water resources has become a global challenge [2]. Cogeneration is defined as the combined production of electricity with other useful forms of energy. By getting more from the same primary energy source, cogeneration results in higher exergetic efficiency, lower pollutant emissions, and lower operational and maintenance costs [3,4].

Fuel cell systems are interesting alternatives (albeit commercially underdeveloped) to conventional power generation systems owing to their high efficiency and low emissions [5]. Among the various types of fuel cells available, solid oxide fuel cells (SOFCs) are key candidates for integration with gas turbines (GTs), owing to their high operating temperature (between 600 °C and 1000 °C). The resulting hybrid SOFC–GT system is a highly efficient power generation unit with the overall electrical conversion efficiency approaching 65% [6]. Adding a heat recovery exchanger also facilitates the possibility of integration of this unit with other thermal systems [7–11]. Accordingly, numerous studies have been carried out on modeling of hybrid SOFC cycles [12–15].

Potable water production is a major untapped application of these hybrid systems—particularly in areas (like the Middle East) which are

---

* Corresponding author. Tel.: +61 413077896.
E-mail addresses: behzad.najafi@polimi.it (B. Najafi), a.shirazi@student.unsw.edu.au (A. Shirazi), mehdi.aminyavari@mail.polimi.it (M. Aminyavari), fabio.rinaldi@polimi.it (F. Rinaldi), Robert.Taylor@unsw.edu.au (R.A. Taylor).

0011-9164/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.desal.2013.11.039

Nomenclature

A	area (m^2)
c_{elec}	electricity unit cost (USD/kWh)
c_f	fuel unit cost (USD/MJ)
c_p	specific heat at constant pressure (kJ/kg K)
CRF	capital recovery factor
c_w	distillate product unit cost (USD/m^3)
$\dot{C}_{env}$	social cost of air pollution (USD/s)
$\dot{C}_{tot}$	total cost rate (USD/s)
e	specific exergy (kJ/kg)
$\dot{E}$	exergy flow rate (kW)
$\bar{e}$	specific exergy (kJ/kmol)
h	specific enthalpy (kJ/kg)
H_b	brine pool height (m)
i	current density (A/m^2), interest rate (%)
k	specific heat ratio
LHV	low heating value (kJ/kg)
$\dot{m}$	mass flow rate (kg/s)
N	operational hours in a year
n	number of desalination stages, system life time (year)
p	pressure (kpa, bar), payback period (year)
PR	thermal performance ratio
$\dot{Q}$	the time rate of heat transfer (kW)
$\bar{R}$	Universal gas constant (kJ/kmol K)
r_p	pressure ratio
s	specific entropy (kJ/kg K)
S/C	steam to carbon ratio
T	temperature (K or °C)
TBT	top brine temperature (°C)
TIT	turbine inlet temperature (K)
T_n	brine temperature in the last stage (°C)
T_s	inlet motive steam temperature (°C)
TTD	terminal temperature difference (°C)
U	overall heat transfer coefficient (kW/m^2 K)
U_a	air utilization factor
U_f	fuel utilization factor
V	voltage (V)
V_v	vapor velocity (m/s)
$\dot{W}$	mechanical work (kW)
X	salt concentration (ppm)
x	molar fraction
X_b	blow-down brine salt concentration (ppm)
X_f	intake seawater salt concentration (ppm)
X_r	recycle brine salt concentration (ppm)
Z	capital cost (USD)
$\dot{Z}$	capital cost rate (USD/s)

Greek symbols

η	efficiency
λ	specific latent heat (kJ/kg)
ρ	density (kg/m^3)
Φ	maintenance factor
ψ	exergetic efficiency

Subscripts

AC	air compressor
ap	approach point
aux	auxiliary
b	brine
BH	brine heater
C	condenser
CC	combustion chamber
CH	chemical
cv	control volume
cw	cooling water
D	destruction
d	distillate product
dc	discharge
ec	economizer
ev	evaporator
f	fuel
FC	fuel compressor
G	electric generator
g	gas
GT	gas turbine
HR	heat recovery
HRSG	heat recovery steam generator
HJ	heat rejection
i	inlet
LMTD	Logarithmic Mean Temperature Difference
MSF	multi stage flash
o	outlet
PH	physical
pp	pinch point
PT	power turbine
REC	recuperator
s	steam
st	stage
suc	suction
sw	seawater
T	turbine
t	tube
tot	total
v	vapor
w	water

facing water scarcity. Since desalination is relatively expensive and requires considerable energy input, cogeneration represents a promising way to lower these barriers to technological uptake [16]. Thermal desalination systems, such as multi stage flash distillation (MSF) and the multi effect distillation (MED), can potentially be coupled with heat recovery steam generators for integration with thermal power plants [17]. Of the two, MSF is a more commonly used desalination technology due to its simple layout and reliable performance. This is especially true in the Middle East where the temperature, salt content, biological activity, and pollution level of the raw water are all relatively high [18].

Accordingly, we propose that for these climates an SOFC–GT plant integrated with an MSF desalination unit can be an appropriate design configuration. To accomplish this, a heat recovery steam generator (HRSG) is utilized to recover the heat wasted from the SOFC–GT system to produce the required motive saturated steam for the MSF unit.

A limited number of studies have investigated the feasibility of integrating fuel cells and desalination units in the past ten years. Hallaj et al. [19], in a conceptual study, demonstrated that the fuel cell based combined heat and power (CHP) systems can be efficiently integrated with reverse osmosis (RO) and MSF desalination units. Their configuration utilized a dual-purpose plant consisting of a molten carbonate fuel cell integrated with an MSF desalination plant. This plant design showed an improvement of 5.61% in global system efficiency. Lisbona et al. [20] investigated different configurations of fuel cell systems integrated with RO and MSF desalination units from energetic and economic viewpoints. In their estimated future scenario, the recovery period of the hybrid RO systems integrated with both MCFC and SOFC was found to be 9 years.

Several studies have also been dedicated to energetic analysis of integrated systems composed of desalination units and conventional power generation systems. These include humidification–dehumidification