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Simulation and exergetic evaluation of CO_2 capture in a solid-oxide fuel-cell combined-cycle power plant

Fontina Petrakopoulou [a,b,*], Young Duk Lee [c,d], George Tsatsaronis [c]

[a] National Technical University of Athens, Iroon Polytechneiou 9, 15773 Athens, Greece
[b] Technical University of Crete, University Campus, 73100 Chania, Greece
[c] Technische Universität Berlin, Marchstr. 18, 10587 Berlin, Germany
[d] Korea Institute of Machinery & Materials, 171 Jang-dong, Yusoneg-gu, Daejeon 305-343, South Korea

HIGHLIGHTS

- An exergetic analysis is used to identify the thermodynamic irreversibilities of a power plant.
- The plant includes a solid-oxide fuel-cell unit and CO_2 capture.
- Additional power generated in the fuel-cell unit enhances the power output of the plant.
- The power plant results in a high efficiency compared both to conventional and other CO_2 capture plants.
- High irreversibilities are found for the solid-oxide fuel cell.

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ABSTRACT

The incorporation of fuel cells into power plants can enhance the operational efficiency and facilitate the separation and capture of emissions. In this paper a fuel-cell unit, consisting of solid-oxide fuel-cell stacks, a pre-reformer, and an afterburner is incorporated into a combined-cycle power plant with CO_2 capture. The thermodynamic performance of the plant is examined using an exergetic analysis and it is compared with a conventional combined-cycle power plant (reference plant) without CO_2 capture, as well as with other plants with CO_2 capture.

The inefficiencies of the chemical reactions taking place in the fuel-cell unit are found to be the main source of exergy destruction among the plant components. However, the additional power generated in the fuel-cell stacks and the afterburner enhances the overall efficiency and compensates for the energy needed for the capture and compression of the carbon dioxide. When compared with the reference plant and with alternative capture technologies, the solid-oxide fuel-cell plant with CO_2 capture operates more efficiently and appears to be a thermodynamically promising approach for carbon capture.

1. Introduction

Solid-oxide fuel cells (SOFCs) are regarded as one of the most promising technologies in the power-generation industry for their high efficiency, high operating temperature, and low emissions that allow various applications for heat and power generation [1,2].

Harvey and Richter [3] first proposed the combination of a Brayton cycle with fuel cells, forming the basis of various studies evaluating different incorporation possibilities of SOFCs into gas turbines systems (e.g., [4–6]). Siemens Energy reported to have successfully demonstrated the concept with a 220 kW unit at the University of California and a 300 kW unit in Pittsburgh. Moreover, Mitsubishi Heavy Industries (MHI) reported to have developed a 200 kW-class SOFC-GT hybrid system combining a tubular type SOFC stack with an internally developed gas turbine. The system was reported to operate successfully with a net electrical efficiency of 52% [7].

The operation of a hybrid SOFC-GT system in partial load conditions was investigated by Calise et al. [8]. In 2003, Onda et al. studied the effcts of different parameters of an SOFC when incorporated into a steam injected gas turbine (STIG) cycle and reported a possible efficiency improvement of 1–3% [9]. In the same year the integration of a humid air turbine (HAT) into an SOFC system was simulated and studied [6,10]. Panopoulos et al. [11] and El-Emam et al. [12] studied the operation of an SOFC in a power plant with coal gasification and a combined heat and power plant (CHP) with biomass gasification, respectively. Akkaya et al. [13] investigated efficiency improvements of an SOFC/GT cogeneration system and Zink et al. [14] researched an SOFC absorption

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* Corresponding author at: National Technical University of Athens, Iroon Polytechneiou 9, 15773 Athens, Greece. Tel.: +30 2107722334; fax: +30 2107723285.

E-mail address: f.petrakopoulou@chemeng.ntua.gr (F. Petrakopoulou).

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Nomenclature

$\dot{E}$	exergy rate (MW)
p	pressure (bar)
T	temperature (°C)
$\dot{W}$	power input/output (MW)
y	exergy destruction ratio (%)

Subscripts

D	exergy destruction
F	fuel (exergy)
gen	power generation
P	product (exergy)
in	input
k	component
L	loss
tot	overall system

Abbreviations

AFB	afterburner
APH	air preheater
C1-C5	compressors
COND	condenser
COOL	cooler
CT	cooling tower
EC	economizer
EV	evaporator
FG	flue gas
GEN	generator
GT	gas turbine
HP	high pressure
HT	high temperature
HRSG	heat-recovery steam generator
IP	intermediate pressure
LP	low pressure
LT	low temperature
NG	natural gas
P	pump
PH	preheater
PR	pre-reformer
SH	superheater
SOFC	solid-oxide fuel-cell
ST	steam turbine

Greek letter

ε	exergetic efficiency

heating and cooling system, finding both technical and environmental advantages of such a coupling. Gadalla and Al Aid [15] reported an efficiency improvement of 5% when combining an SOFC with a PEMFC (polymer electrolyte membrane fuel cell) in a GT system. A trigeneration plant combining an SOFC with an organic Rankine cycle (ORC) was studied by Al-Sulaiman et al. [16] showing relatively promising results. Lastly, Rajashekara [17] studied the operation of various hybrid plants with fuel cells, including the coupling of an SOFC with a thermo-photovoltaic power generation unit.

Although various studies on SOFC applications and integration exist, large-scale SOFCs are not yet commercially available and the technology cannot be considered fully developed. Additionally, fuel-cell technology is associated with high costs and various technical problems, such as fuel gas desulfurization, reforming and short stack working life. Nevertheless, the relatively high efficiencies and the lower emissions achieved with fuel cells make them attractive from an environmental viewpoint [18]. Overall, when compared to other alternatives, combining hybrid GT/SOFC systems with CO_2 capture is an option to achieve very low emissions with relatively high efficiency [19].

Carbon capture and storage (CCS) is suggested as a means for mitigating climate change linked to the combustion of fossil fuels [20,21]. Thus, it is important to evaluate the feasibility of alternative CCS technologies [22–25]. CO_2 capture can be separated into three main groups: post-combustion, pre-combustion and oxy-fuel combustion, depending on the oxidant used in the combustion, and on whether the capture is realized before or after the combustion.

In this paper, we present an oxy-fuel, large-scale combined-cycle power plant, in which the combustion chamber is replaced by an integrated pressurized SOFC unit [26–28]. The plant includes CO_2 separation and compression and its structure is based on a conventional reference combined-cycle power plant without emission reduction [29–31]. The thermodynamic performance of the CO_2 capture plant is examined using an exergetic analysis, with which irreversibilities within components and component efficiencies are calculated. The operation of the plant is compared to that of the conventional reference plant, as well as to other CO_2 capture technologies [32]. Finally, important strategies that would improve the overall plant performance are discussed.

2. Methodology

2.1. Principles of an exergetic analysis

Exergy is the maximum theoretical work obtainable from a thermal system, as the system is brought into thermodynamic equilibrium with the environment, while interacting with this environment only [33]. Neglecting nuclear, magnetic, electrical and surface tension effects, the total exergy of a system, $\dot{E}_{sys}$, consists of four parts: physical, kinetic, potential and chemical exergy:

$$\dot{E}_{sys} = \dot{E}^{PH} + \dot{E}^{KN} + \dot{E}^{PT} + \dot{E}^{CH} \tag{1}$$

Here, the kinetic and potential exergy are neglected because the system is considered to be at rest, relative to the environment. The specific physical exergy of a material stream is obtained from:

$$e^{PH} = (h - h_0) - T_0(s - s_0) \tag{2}$$

where h_0 and s_0 are the specific enthalpy and entropy, respectively, of the stream being considered at the reference state, and h and s are the specific enthalpy and entropy at the given thermodynamic state. The chemical exergy per mole of gas of a mixture of n gases is calculated with Eq. (3), where e_i^{CH} and x_i are the standard molar chemical exergy and the mole fraction of each substance i, respectively.

$$e^{CH} = \sum_{i=1}^{i=n} x_i e_i^{CH} + RT_0 \sum_{i=1}^{i=n} \ln(x_i) \tag{3}$$

The total exergy rate of stream j is calculated by multiplying its total specific exergy, $e_j = e^{PH} + e^{CH}$ with its mass flow rate, $\dot{m}_j$:

$$\dot{E}_j = \dot{m}_j e_j \tag{4}$$