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Exergetic and exergoeconomic evaluation of a solid-oxide fuel-cell-based combined heat and power generation system

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ABSTRACT

Exergetic and exergoeconomic evaluations have been carried out for a 100 kW-class solid-oxide fuel-cell-based combined heat and power generation system, to find out the measures that would improve its efficiency, and, more importantly, its cost effectiveness. The exergoeconomic analysis is an appropriate combination of an exergetic analysis and an economic analysis; through exergoeconomics, we obtain the real cost associated with each stream and with the inefficiencies within each component in a system.

For the analyses, the exergies of fuel and the exergies of product for all components have been defined. Subsequently, the exergetic efficiency of each component has been evaluated. By combining the results obtained from an economic analysis with the results of the exergetic analysis, the cost structure of the overall system has been figured out. The components, showing higher exergoeconomic factors such as SOFC stack, fuel blower, heat recovery water pump, and inverter, need reduction of investment cost, even if the associated efficiency would decreased because of this cost reduction. For the components, exhibiting lower exergoeconomic factors such as integrated reformer, fuel/water pre-heater, and air pre-heater, the main focus should be on efficiency improvements, even if higher investment expenditures would be associated with such improvements.

1. Introduction

Fuel cells have received much attention for their potential use in decentralized power generation systems, mainly due to their relatively high efficiency even at part load, low local emissions, and low noise level [1]. Among several types of fuel cells, the solid-oxide fuel cell (SOFC) is considered to be the most promising type for decentralized power generation applications, in the range from tens of kilowatts to several megawatts [2]. An SOFC operates at high temperature, ranging from 700 to 1000 °C, and consequently the electrochemical conversion takes place efficiently, with relatively low thermodynamic losses. Furthermore, the high-temperature heat it produces can be utilized both for thermal energy recovery and for additional power generation [3].

During the recent decades, continuing research on SOFCs has been carried out and much progress has been achieved in raw material development, stack development, and demonstrations of prototype systems [4–7]. In spite of the significant progress, several barriers still prevent the full commercialization of SOFC systems: These systems first, exhibit performance degradation, which should be minimized [8]. Second, the system structure should be optimized to guarantee robust operation [9]. Finally, and most importantly, the cost should be reduced not only from the manufacturing but also from the operational standpoint [10].

As an analysis tool for improving energy conversion systems, exergy-based methods have been developed [11–13] and applied to a wide range of applications [14–17], including fuel-cell-based power generation systems [18–31]. An exergetic analysis identifies the location, magnitude and sources of thermodynamic inefficiencies in an energy conversion system [11]; this information is then used to improve the thermodynamic performance of the analyzed system. The same information can also be used to optimize the operating conditions. The early application of exergy-based methods to SOFC systems started with fundamental thermodynamic considerations; Ratkje and Møller-Holst [18] compared various types of fuel cells using the results from exergetic evaluations. Since then, systematic investigations of complex fuel cell systems [19–23] have followed; Bedringas et al. [19] suggested a general exergetic analysis procedure applicable to SOFC systems; Hotz et al. [20] calculated the exergy destruction rate within each component in a micro-SOFC system; Douvartzides et al. [21,22] carried

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Nomenclature

C	cost associated with an exergy stream ($)
c	specific cost of exergy, cost per unit exergy ($/MJ)
E	exergy (kJ)
e	specific exergy (kJ/kg)
f	exergoeconomic factor (–)
f_n	efficiency correction factor for pump (–)
LHV	lower heating value (kJ/kg)
LC	levelized cost ($/yr)
m	mass (kg)
p	pressure (bar)
PEC	purchased equipment cost ($)
$Q_{thermal}$	thermal energy (heat) (kJ)
r	relative cost difference (%)
T	temperature (K)
V	voltage, or voltage loss (V)
W	power production or power consumption (kW)
y	exergy destruction ratio (%)
Z	cost associated with investment expenditures ($)

Greek symbol

ε	exergetic efficiency
η	energetic efficiency (%)
τ	capacity factor of plant operation

Subscripts

AB	air blower
AC	alternating current
act	activation voltage loss
BOP	balance of plant
CC	catalytic combustor (in plant description), or carrying charges (in economic calculations)
cell	cell of SOFC
con	concentration voltage loss
DC	direct current
ER	external reformer
F	exergy of fuel
FB	fuel blower
fuel	fuel (external fuel to the system)
HEX1	pre-heater for fuel and water
HEX2	pre-heater for cathode air
HRWP	water-pump for heat recovery unit
INV	inverter
IR	internal reforming part
j	*j*-th stream
k	*k*-th component
L	exergy loss
Nernst	Nernst potential
net	net power of the system
ohm	ohmic voltage loss
O&M	operation and maintenance
P	exergy of product
SOFC	SOFC
thermal	thermal efficiency or thermal energy
tot	overall system
WP	water pump for reformer
Z	investment costs

Superscripts

·	time rate
CC	carrying charges (for economic calculations)
CH	chemical exergy
O&M	operation and maintenance
PH	physical exergy

out an optimization for an ethanol-fueled SOFC system using exergy concepts; Calise et al. [23] applied the exergy concept to computational fluid dynamics, calculating the exergy destruction distribution over the SOFC domain. In addition, exergy-based methods have been applied to advanced concepts of SOFC power generation systems [24–31].

When an energy conversion system is improved using results obtained from an exergetic analysis, economic considerations should also be taken into account; this enables cost optimization, which should be simultaneously studied together with the efficiency improvements. In this sense, an exergoeconomic analysis, which can be regarded as an exergy-aided cost reduction approach [11], is the most effective method in identifying measures that would reduce the overall cost of the final product(s).

An exergoeconomic analysis is a synergetic combination of an exergetic analysis and an economic analysis; its goal is to obtain the real costs associated with each stream and each component in a system (including the costs associated with the exergy destruction within each component [32]).

For the past few decades, an exergoeconomic analysis was successfully applied to various energy systems and results were reported for conventional power generation systems [34–36], CCS technologies [37–40,33], hydrogen production plants [40–42], refrigeration machines [43], microCHP systems [44–46], buildings [47], and waste-water treatment plants [48]. Also cost reduction based on exergoeconomics has been successfully conducted, for example [49–51].

In this paper, a solid-oxide fuel-cell-based (SOFC) combined heat and power (CHP) system has been investigated using an exergetic and an exergoeconomic analysis. Through the exergetic analysis, the magnitude of exergy destruction of each component has been quantified, and from that it was determined which components needed improvement from a thermodynamic viewpoint. Based on the results obtained from the exergoeconomic analysis, the cost structure of the overall system has been analyzed, and suggestions are made for improving its cost effectiveness. To obtain useful results from the exergetic and exergoeconomic analyses, the purpose of the equipment items and the entire system should be defined well. In this regard, this paper has focused on the development of a general procedure applicable to an SOFC power generation system and its application to an SOFC CHP system. The system chosen for analysis was a 100 kW-class solid-oxide fuel-cell-based combined heat and power system, generating both electricity and steam simultaneously.

2. Description of the analyzed system

2.1. Description of the system layout

A schematic diagram of the analyzed system is shown in Fig. 1. The system consists of a 100 kW-class SOFC stack, a reformer, a catalytic combustor, heat exchangers, pumps, blowers, an inverter, and a heat recovery steam generator (HRSG). The operating pressure and temperature of the SOFC stack are assumed to be atmospheric pressure and 850 °C [52,53], respectively. Fuel and water are preheated through a heat exchanger (HEX1) before being supplied to an external reformer (ER). After being partially reformed in the external reformer, the syngas mixture is supplied to the anode of the SOFC stack. The remaining un-reformed fuel is reformed within the anode of the SOFC stack; the required heat