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Exergoenvironmental comparison of internal reforming against external reforming in a cogeneration system based on solid oxide fuel cell using an evolutionary algorithm

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Two different arrangements of a system including a cogeneration plant based on solid oxide fuel cell with internal reforming (IR-SOFC) and solid oxide fuel cell with external reforming (ER-SOFC) for producing power and hot water are modeled and analyzed thermodynamically. Also, in order to determine the optimal values of design parameters including SOFC inlet temperature, current density, steam-to-carbon ratio, and fuel utilization factor, an evolutionary algorithm for multi-objective optimization purposesis applied. For both systems, two objective functions including the exergy efficiency and CO_2 gas emission (EMI) in kg/MWh, with the aim of maximizing the exergy efficiency and minimizing the EMI are considered. The optimization results revealed that at the final optimal design point, the value of the exergy efficiency of the cogeneration system based on IR-SOFC is about 9.6% more than that of the system based on ER-SOFC. Moreover, the amount of EMI in the first configuration (cogeneration system based on IR-SOFC) is about 1.4% lower than that of the second one (cogeneration system based on ER-SOFC).
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1. Introduction

Energy crisis and global warming have been the most important and an undeniable issue of recent decades. Limited natural resources and increasing rate of world population make this crisis more important. According to the World Energy Outlook published by the International Energy Agency (IEA), the world's total electricity consumption would be doubled between 2003 and 2030. This report predicted that the share of fossil fuels as energy supplies for electricity generation will remain constant at nearly 65%. Power generation is responsible for half of the increase in global greenhouse gas emissions over the projection period. As a result of all these problems, sustainability considerations should be involved in all major energy development plansall over the world. There are various definitions for sustainability. Probably the simplest one is that sustainable activities are the activities that help existing generation to meet their needs without destroying the ability of future generations to meet theirs [1].

Fuel cells are an efficient approach for energy conversion. They can produce electricity directly from fuel and oxidant; hence emission from fuel cells is lower than that in fuel combustors. In conventional power generation systems, the heat released through the combustion process is converted to mechanical energy. Whena conventional thermal engine operates under Carnot cycle, the maximum thermal efficiency of the system could be achieved. The efficiency of this system is related to the ratio of the heat source and heat sink absolute temperatures. However, a fuel cell is an energy conversion device that converts the chemical energy of a fuel directly to the electrical energy and heat, without needing for direct combustion as an intermediate step. It gives much higher conversion efficiencies than conventional thermo-mechanical methods. In fuel cell systems, mixture of a gaseous fuel (e.g. hydrogen or hydrocarbon fuels) and an oxidant gas (e.g. oxygen in the air) move forward to electrodes and half-cell reactions occur on the anode side and cathode side, respectively. During these electrochemical reactions, the active charge carrier species exchange through an ion conducting electrolyte. In this way, electrons are released into external circuit to produce electricity. However, unlike a battery, a

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fuel cell does not require recharging. A fuel cell operates as long as both fuel and oxidant are supplied to the electrodes and is environment friendly, with negligible influence exerted on the natural environment [2,3].

Among different kinds of fuel cells, the solid oxide fuel cell (SOFC) is very demanding from materials standpoint and has potential advantages and competitiveness in the following aspects [4,5]:

- It is the most efficient fuel cell in terms of electrical power generation. In addition, the high operating temperature of SOFCs produces high quality heat byproduct which can be used for cogeneration or combined cycle applications. This can further increase the overall energy efficiency.
- It is flexible in the choice of fuels such as hydrocarbon fuels, e.g., natural gas.
- SOFCs do not need expensive noble metals that could be issues in resource availability and cost.
- Any carbon monoxide produced is converted to carbon dioxide at the high operating temperature; therefore SOFCs have very low emissions in exhaust gases.

Hydrogen is an element with a high energy density but is not found free in the nature. So generally, hydrogen used in fuel cell must be produced from fossil fuels to be converted to electricity with high efficiency**.** In power generation systems based on SOFC, hydrogen is produced from methane reforming process in a reformer fed with steam, which is called external reformer. Also, due to the high operation temperature of SOFC and steam produced during the chemical process, SOFC can be used to internally reform the methane to produce hydrogen. This means that first, methane fuel enters directly into the SOFC and hydrogen is directly extracted. This type of fuel reforming process is called as the internal reforming process.

A hybrid solid oxide fuel cell-gas turbine (IR-SOFC-GT) power system was investigated with exergy analysis by Calise et al. [6], for various operating conditions and parameters. They demonstrated that, for a 1.5 MW plant, an energy efficiency close to 60% can be achieved applying suitable values of the most important design parameters; in particular, the operating pressure and cell current density.

Ghanbari [7] assessed a methane-fed internal reforming solid oxide-gas turbine (IRSOFC-GT) power generation system in terms of energy and entropy. She found that increasing the fuel flow rate does not have a significant effect on system performance. Also, she concluded that although fuel cell is an efficient device it is the most important source of exergy destruction in the proposed system.

Musa et al. [8] performed energy analysis on a molten carbonate fuel cell (MCFC) power system with internal and external reforming. As a comparison, it was observed that the value of energy efficiency of the MCFC system with external reforming was lower than that of the MCFC system with internal reforming.

Akkaya et al. [9] carried out an analytical performance study of a tubular solid oxide fuel cell (TSOFC) module fed by methane. For upgrading the fuel, they applied internal reforming process. They found that, among the components, the most important exergy destruction rates were associated with fuel cell group and afterburner, respectively. These authors in another paper [10] conducted energy and exergy assessments of a SOFC power generation system fed by hydrogen. The performance of fuel cell system with hydrogen fuel was analyzed based on a new performance benchmark named exergetic performance coefficient (EPC). Results showed that design insights of SOFC systems can be efficiently improved when conventional energetic analyses are supplemented with EPC benchmark.

The influences of direct internal reforming (DIR) in a solid oxide fuel cell on thermal fields were reported by Dehimi et al. [11]. Their numerical study proved that the best conditions for direct internal reforming (DIR) in a planar SOFC system fed by methane were at a high temperature (1273 K).

Meng [12] developed a 2D numerical model to simulate the performance of SOFC system operating at the temperature of 1073 K and fed by CO_2 and CH_4 mixtures. The main chemical reactions in the numerical model consisted of methane carbon dioxide reforming (MCDR), methane steam reforming (MSR) and reversible water gas shift reaction (WGSR). The analysis showed that at a CH_4/CO_2 molar ration of 50/50, MCDR and reversible WGSR significantly affected the fuel cell performance while MSR was negligibly small.

De lorenzo et al. [13] developed zero-dimensional and steady simulation model of a syngas-fed SOFC system in cogenerate configuration and implemented in the Matlab software by which the SOFC system performances were evaluated. Ebrahimi et al. [14] proposed a newsystem combining three technologies of micro gas turbine, solid oxide fuel cell and organic Rankine cycle to produce electrical power in micro scale. Meratizaman et al. [15] performed complete thermodynamic simulation of a SOFC-GT power system 300–1000 kW (size of SOFC). Saisirirat et al. [16] simulated a detailed thermodynamic model of SOFC and gas turbine hybrid system and few arrangements of the combined or hybrid plants are proposed and analyzed. Buonomano et al. [17] presented a comprehensive review of the possible arrangements of hybrid power systems based on the combination of solid oxide fuel cells and gas turbine technologies. These authors employed simple economic models in their investigations in order to determine the price of the generated electricity, and their considered hybrid systems consisted of gas turbines and pressurized fuel cells. An optimal configuration for a SOFC-GT hybrid system based on thermoeconomic modeling was performed by Pirkandiet al. [18]. The authors presented four different layouts of direct hybrid systems with pressurized and atmospheric fuel cells. As a comparison, it was found that the hybrid system with one pressurized fuel cell was better than the others.

To the best of the author's knowledge, multicriteria optimization based on the exergy and environmental principles has not been conducted for comparison of two different configurations of a SOFC-cogeneration system. The potential SOFC-cogeneration systems considered are cogeneration plant based on SOFC with internal reforming (IR-SOFC) and SOFC with external reforming (ER-SOFC). SOFC inlet temperature (T_i), fuel utilization factor (U_f), current density (J) and steam-to-carbon ratio (r_{sc}) are considered as the design parameters. Specifically, the exergy efficiency as the first objective function is maximized while the CO_2 gas emission (EMI) as the second target is minimized. The optimization results achieved for both objective functions are compared to identify the superior optimization strategy.

2. Systems description and assumptions

The schematic diagrams of the two considered systems including a cogeneration system based on IR-SOFC and ER-SOFC are shown in Figs. 1 and 2, respectively. The first system, as shown in Fig. 1, consists of a SOFC stack with internal reforming, an afterburner, a DC/AC invertor, water pumps, a mixer, compressors and heat exchangers. In the second system, as depicted in Fig. 2, the external reformer is used while the other elements are the same as the first system. In these layouts, the purpose is to produce electrical power in the SOFC stack and hot water in the heating process heat exchanger. The system operation according to Fig. 1 can be summarized as follows:

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