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Research paper

Greenhouse gas emission and exergy analyses of an integrated trigeneration system driven by a solid oxide fuel cell

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HIGHLIGHTS

- A novel trigeneration system driven by a solid oxide fuel cell is analyzed.
- Exergy and greenhouse gas emission analyses are performed.
- Four special cases are considered.
- An enhancement of up to 46% is achieved in exergy efficiency.
- The CO_2 emission drops to a relatively low value for the tri-generation case.

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ABSTRACT

Exergy and greenhouse gas emission analyses are performed for a novel trigeneration system driven by a solid oxide fuel cell (SOFC). The trigeneration system also consists of a generator-absorber heat exchanger (GAX) absorption refrigeration system and a heat exchanger to produce electrical energy, cooling and heating, respectively. Four operating cases are considered: electrical power generation, electrical power and cooling cogeneration, electrical power and heating cogeneration, and trigeneration. Attention is paid to numerous system and environmental performance parameters, namely, exergy efficiency, exergy destruction rate, and greenhouse gas emissions.

A maximum enhancement of 46% is achieved in the exergy efficiency when the SOFC is used as the primary mover for the trigeneration system compared to the case when the SOFC is used as a standalone unit. The main sources of irreversibility are observed to be the air heat exchanger, the SOFC and the afterburner. The unit CO_2 emission (in kg/MWh) is considerably higher for the case in which only electrical power is generated. This parameter is reduced by half when the system is operates in a trigeneration mode.

1. Introduction

Using waste heat from a primary mover to operate a subsystem is one way to enhance the overall performance of a thermal plant. In such a system, useful energy can be obtained through the utilization of waste heat. For instance, trigeneration systems have received much attention in recent years, as they often have high efficiencies as well as low operating costs and greenhouse gas emissions. Trigeneration systems are capable of producing electricity, cooling and heating, and in some cases desalinated water. Such systems are also often referred to as a combined cooling, heating and power (CCHP) plants.

The electrical power produced by a trigeneration system is based on one or more primary drivers, such as a diesel engine, a gas turbine or a fuel cell. Fuel cells are highly efficient as they convert a fuel's chemical energy directly to electrical energy electrochemically, and thus without being limited by the Carnot efficiency.

Using fuels such as methane, the SOFC is considered by many to be an important emerging technology for electricity production. It operates at high temperature and rejects high quality heat, so it is commonly combined with a gas turbine (GT) or an organic Rankine

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cycle (ORC) as a bottoming cycle. In recent years, much research has been carried out on simulating the performance of SOFC-GT hybrid power plants [1–4], integrated SOFC-ORC power plants [5,6] and combined SOFC-Stirling hybrid plants [7,8]. However, there is a lack of research on the performance of cogeneration/trigeneration power plants based on SOFCs, especially with environmental impact assessments.

A natural gas fueled 1 kW residential combined heating and power (CHP) system based on solid oxide fuel cell (SOFC) was established by Xu et al. [9]. They presented conceptual design and mathematical analysis. These authors also the influences of decisive design parameters on the system performance and selection principle of design-point condition investigated.

Chen et al. [10] performed an economic analysis of a solid oxide fuel cell cogeneration/trigeneration system for hotels in Hong Kong. Energy consumption profile of Hotel ICON was adopted for a case study. Existing products of SOFC server and absorption chiller was chosen to configure the system. The analysis demonstrated that the payback period is less than 6 years with the Government subsidy at 50% of the overall system cost for a trigeneration plant.

Weber et al. [11] conducted a detailed analysis of the CO_2 emission and product cost of a SOFC-based trigeneration system for an office building. They reported a 30% reduction in CO_2 emissions at an approximate cost increase of 70% compared to a conventional system.

A trigeneration plant driven by a combination of a SOFC and a gas turbine was examined from the viewpoints of thermoeconomics and environmental impact by Burner et al. [12]. The plant consisted of half, single or double-effect chillers, a heat pump, an additional gas boiler, a heat recovery boiler, a compression chiller and a cooling system. They demonstrated that the SOFC-GT system is attractive economically and environmentally. These authors also carried out a multi-objective optimization based on a multi-criteria evolutionary algorithm focusing on the annual total product cost and annual CO_2 emission rate.

Liu et al. [13] proposed a trigeneration plant consisting of a solid oxide fuel cell with internal-reforming (IRSOFC) and a zeolite/water adsorption chiller. They also analyzed numerically the performance of the system under various operating conditions.

Yu et al. [14] analyzed a total energy system consisting of a solid oxide fuel cell and an absorption chiller to provide power, cooling and/or heating, simultaneously. They found that, both the electrical and total efficiencies are maximized at a special value of fuel utilization coefficient.

Al-Sulaiman et al. [15] proposed a trigeneration system and analyzed its performance from the viewpoint of the first law of thermodynamics. The proposed system consists of a SOFC, an ORC, a heat exchanger and a single-effect absorption chiller. They concluded that the efficiency of the trigeneration plant is at least 22% higher than that of the stand-alone power plant. These authors in another paper [16] reported an exergy analysis for a proposed trigeneration system, and concluded that the exergy efficiency is enhanced by 3–25% when the trigeneration plant is used instead of the stand-alone power cycle.

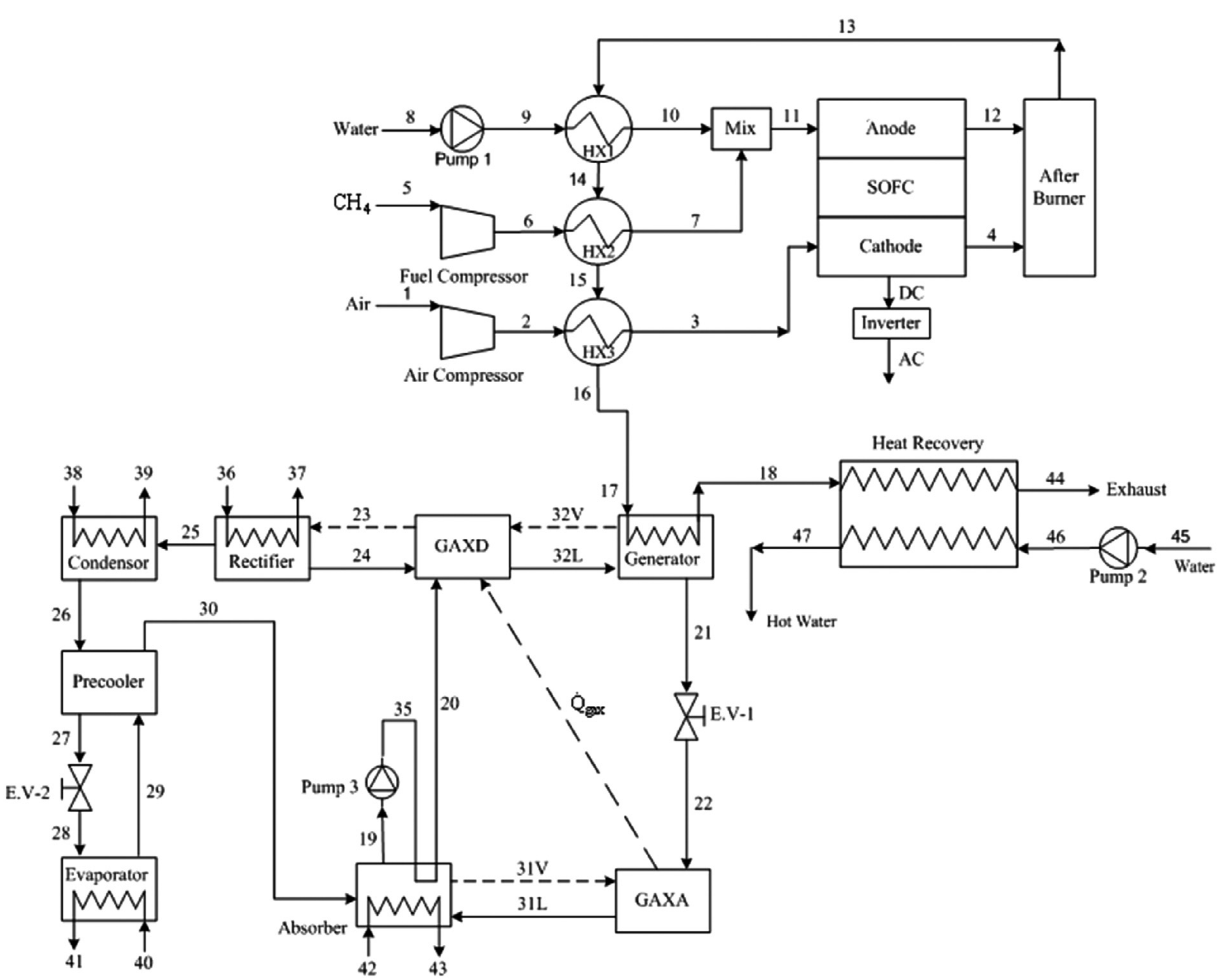

Fig. 1. Schematic diagram of the proposed trigeneration system.