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Energy and exergoeconomic evaluation of a new power/cooling cogeneration system based on a solid oxide fuel cell

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ABSTRACT

A new cogeneration system consisting of a hydrogen-fed SOFC (solid oxide fuel cell), a GT (gas turbine) and a GAX (generator-absorber-heat exchange) absorption refrigeration cycle is proposed and analyzed in detail. The electrochemical equations for the fuel cell and thermodynamic and exergoeconomic relations for the system components are solved simultaneously with EES (Engineering Equation Solver) software. Through a parametric study, the influences of such decision parameters as current density, fuel utilization factor, pressure ratio and air utilization factor on the performance of the system are studied. In addition, using a genetic algorithm, the system performance is optimized for maximum exergy efficiency or minimum SUCP (sum of the unit costs of products). The results show that, the exergy efficiency of the proposed system is 6.5% higher than that of the stand-alone SOFC. It is also observed that the fuel cell stack contributes most to the total irreversibility. The exergoeconomic factor, the capital cost rate and the exergy destruction cost rate for the overall system are observed to be 27.3%, 10.63 \$/h and 28.3 \$/h, respectively. It is observed that for each 6 \$/GJ increase in the hydrogen unit cost, the optimum sum of the unit costs of products is increased by around 62.5 \$/GJ.

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1. Introduction

The negative effects such as depletion of energy resources, global warming and long-term increases in energy prices have spurred efforts to find new and more beneficial ways to convert the chemical energy of fuels to electricity, cooling and heating. Fuel cells can support such efforts because of their many advantages, which include high efficiency, low emissions, high power density, ability to produce energy locally, ease of installation and operation, and ability to use a variety of fuels [1]. It is also possible to combine high temperature fuel cells, such as the SOFC (solid oxide fuel cell) or the MCFC (molten carbonate fuel cell), with other power plants such as gas turbine or other bottoming cycles to obtain higher efficiencies. Such systems can achieve efficiencies of 70% or higher [2].

Many researchers have studied various combined systems based on fuel cells, especially SOFCs [3–13].

Bakalis et al. [14] analyzed three different SOFC hybrid power systems with zero-CO_2 emission and reported that capturing the CO_2 in these systems does not lower their efficiencies much. Using life cycle assessment method, Lee et al. [15] assessed the environmental impact of a SOFC-based CHP system and concluded that the manufacturing stage and disposal stage have small contributions to the total environmental impact. Costamagna et al. [16] analyzed the design and off-design performance of a hybrid system consisting of a recuperated micro gas turbine and a high temperature solid oxide fuel cell and reported thermal efficiencies over 60% at the design point and over 50% at part load conditions for the system. Granovskii et al. [17] thermodynamically compared using numerical approaches two combined SOFC-gas turbine systems, and concluded that, for the same SOFC stack, the scheme with recycling is more efficient but the scheme with steam generation generates more power. Using two-stage gasification, Bang-Møller et al. [18] evaluated the performance of a hybrid plant consisting of a solid oxide fuel cell and a micro gas turbine for producing heat and power. Under optimized conditions, the plant can produce 290 kW of electrical power with an efficiency of 58.2%. Using the Lagrange Multipliers method, Cheddie [19] developed a thermo-economic

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model to simulate the performance of an indirectly coupled SOFC-gas turbine hybrid power plant and reported, under optimized conditions, a breakeven unit energy cost of USD (2011) 4.54 ¢/kWh when the output power was 18.9 MW with an energy efficiency of 48.5%. Using two methods for hydrogen separation, Becker et al. [20] examined the design and performance of a combined heat, hydrogen and power production system incorporating a methane-fueled, 1 MW SOFC, for steady state conditions. They reported that the expected cost of SOFC-based distributed hydrogen production is on par with other distributed hydrogen production technologies, such as natural gas reforming or electrolysis. Rokni [21] designed a hybrid SOFC-Stirling plant with a power capacity of up to 10 kW and an efficiency of 60%, for use with alternative fuels. Bellomare et al. [22] studied two configurations of municipal solid waste gasification plants integrated with a SOFC and a gas turbine, and showed that, under optimized conditions, they achieve a thermodynamic efficiency of approximately 52% for the plant with regenerative gas turbine. Chen et al. [23] investigated the economics of a cogeneration/trigeneration system comprised of a SOFC and an absorption cooling system for residential use in Hong Kong. Akikur et al. [24] modeled a cogeneration system using solar energy and SOFC technology, and reported the overall system efficiency for the solar-SOFC mode to be 23%. Sanaye et al. [25] performed a multi-objective optimization of a hybrid SOFC-micro gas turbine system using a genetic algorithm. It was observed that cell current density, among other system design parameters, plays an important role in balancing system cost and performance. Ranjbar et al. [26] studied a trigeneration system consisting of a SOFC, a GAX absorption refrigeration and a heat recovery steam generator, and showed that the energy efficiency of the trigeneration system is at least 33% higher than that of the SOFC and that the main exergy destructions occur in the air heat exchanger, the SOFC and the afterburner.

1.1. *Configuration optimizing*

In optimizing the configuration for multi-generation system, especially when different cycles are combined, the temperature matching between the sub-systems plays an important role. As this temperature matching brings about less exergy destruction and consequently more efficient system. This point has been considered by the researchers in combining the SOFC with GT, as concluded from the above discussion. The exhaust gas from the gas turbine however, possesses a considerable amount of energy, so that it can be utilized to run another bottoming cycle to produce cooling. In this paper a new combined SOFC-GT-GAX system is introduced and investigated in detail from thermodynamic and exergoeconomic viewpoints. This plant produces electrical power and cooling as its main and secondary products, respectively, and can be useful in practical applications, since a considerable amount of cooling is produced from the SOFC-GT waste heat. The system performance is simulated and assessed by applying the conservation of mass and energy, exergy balances and exergoeconomic relations to each system component. A detailed electrochemical analysis is performed for the fuel cell to calculate its voltage and electrical power generation. In addition, a parametric study is carried out to investigate the effects on system performance of the main decision parameters. Finally the system performance is optimized for maximum exergy efficiency or minimum SUCP.

2. System description and assumptions

A schematic of the proposed system is shown in Fig. 1. This system includes air and fuel compressors, heat exchangers, a solid oxide fuel cell stack, an inverter, an afterburner, a gas turbine and a GAX absorption refrigeration cycle.

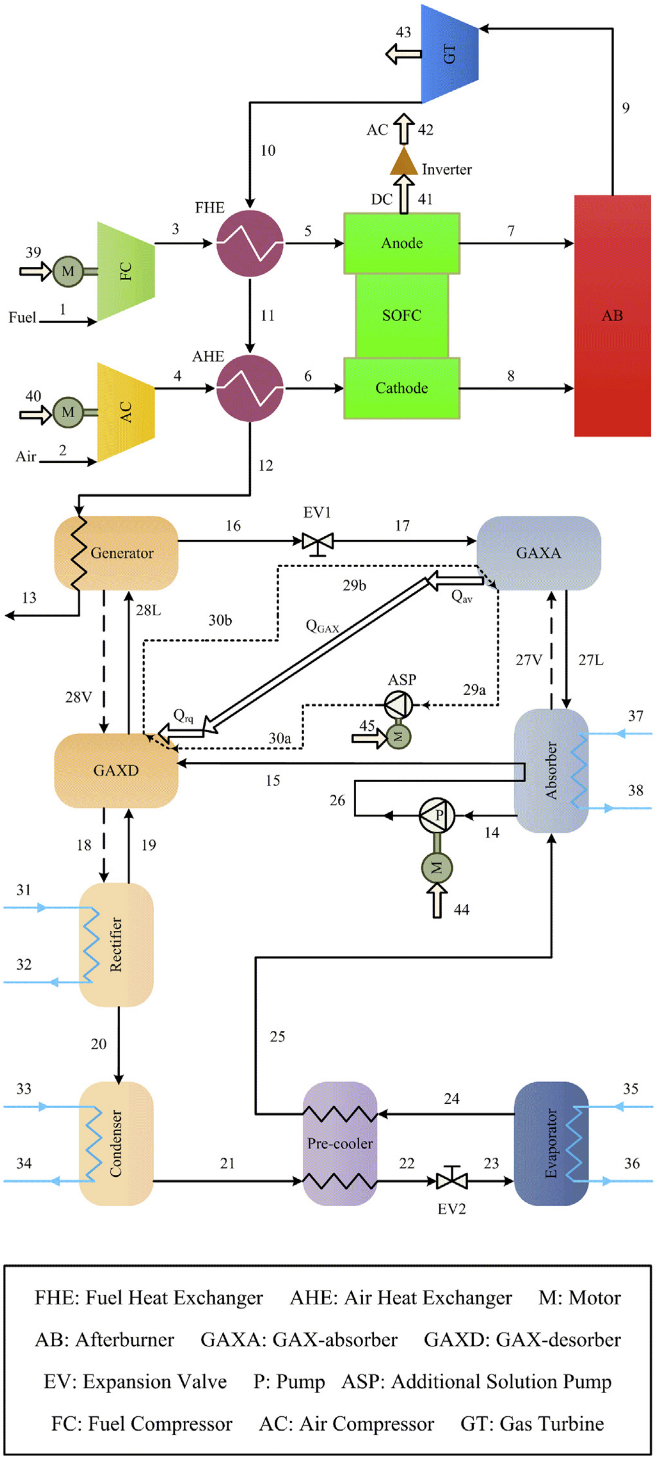

Fig. 1. Schematic diagram of the electrical power/cooling cogeneration system.

The inlet fuel and air are pressurized by the fuel and air compressors, respectively before entering the fuel cell. As indicated in Fig. 1, the pressurized fuel and air are heated separately, by means of the combustion gases exiting the gas turbine, before they enter the fuel cell stack. There, the electrochemical reaction between the hydrogen and oxygen generates electrical current (DC), which is converted to alternating current (AC) by the inverter. As the electrochemical reaction is exothermic, the stack temperature rises. A

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