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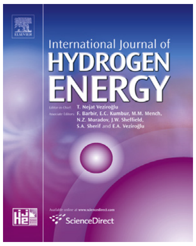

Exergetic and exergoeconomic evaluation of a trigeneration system based on natural gas-PEM fuel cell

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ABSTRACT

In this study, the performance of a novel micro-combined heat and power generation system (mCHP) based on PEM fuel cell is analyzed from exergoeconomic aspect of view. The main components of the system are a 10 kW PEM fuel cell stack, a thermal energy storage tank based on phase change material, an absorption chiller, and a steam reformer that operates using natural gas. The main objective of this study is to perform an exergoeconomic evaluation on a PEM fuel cell system integrated with absorption chiller, which is designed to supply electrical energy, hot water and space cooling for a residential application. The effects of working temperature, pressure, current density, and heat source temperature of generator on the performance of the system are studied. The results reveal that besides operating pressure and temperature, fuel cell voltage can significantly affects the exergy cost of the system. It is concluded that by increasing the heat source temperature, the exergy cost of chilled water decreases and the COP of absorption chiller can be increased by more than 30%. Also, it is found that the PEM fuel cell, storage tank, and evaporator have the highest exergy destruction cost rates, respectively.

Introduction

Quick growth of population and industrial plants has increased the demand for energy systems with high efficiency and low environmental pollution. Concurrent production of electrical energy and heat is a viable method that is being developed, rapidly. This method is implemented using combined heat and power (CHP) systems that have relatively higher energy efficiency than conventional power plants [1]. CHP systems are usually categorized based on their electrical power capacity into three major groups including small scale CHP, large scale CHP, and micro CHP (mCHP) systems. These subcategories have nominal capacity of less than 1 MW, more than 1 MW and less than 50 kW, respectively [2]. Combined heat and power systems have various primary drivers such as gas turbines, combustion engines, fuel cells and Stirling engines [3].

Extensive investigations have been published on fuel cell based CHP systems that are suitable for residential application. Pahon et al. developed a method to study the durability of a PEM fuel cell micro-cogeneration system. The results of their long-term tests indicate that the global voltage degradation rate does not change when the operation time is reduced from 1000 h to 500 h [4]. Lee et al. carried out exergy and

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exergoeconomic analyses on a 100 kW-class solid oxide fuel cell-based combined heat and power generation system. The results of their study show that SOFC stack, fuel reformer, energy recovery heat exchanger, water pump and inverter have higher exergy cost rates than other components, and their investment cost should be reduced even if the associated efficiency may decrease [5]. Zuliani et al. applied a simulation model and used experimental data to evaluate the performance of a 1 kW High Temperature PEM (HT-PEM) fuel cell cogeneration system that uses natural gas. The results indicate that the system electrical efficiency is 26% and overall energy efficiency is 78% at design load. Also, their results show that the energy efficiency of the fuel cell system is higher than other cogeneration systems based on internal combustion engines or gas turbine [6].

Romero-Pascual et al. developed a model for a HT-PEM-based micro-combined heat and power fuel cell system that uses methanol [7]. Their results show that by increasing the fuel cell temperature, the power system efficiency is improved with less methanol and air inlet mass flow rates. The system has demonstrated electrical efficiency of 24% and overall CHP efficiency of about 87%. In another study, Najafi et al. presented a new configuration of a micro CHP based on HT-PEM fuel cell instead of a low temperature PEM fuel cell. The electrical efficiency and the primary energy saving index for the proposed are calculated as 29.21% and 17.5%, respectively. However, the same parameters for the low temperature system are considerably lower than those obtained for HT-PEM based plant [8].

An energy and exergy analysis of a CHP system based on PEM fuel cell for residential application is carried out by Barelli et al. [9]. The optimum operating conditions in terms of temperature and relative humidity are reported on the basis of the second law efficiency, and the cogeneration system efficiency of 58% is obtained. In another study, Barelli et al. [10] compared two mCHP units based on PEM fuel cell and solid oxide fuel cell for residential applications using energy and exergy analyses. The result of this study revealed that the PEM fuel cell based CHP system has higher exergy efficient, because it operates at atmospheric pressure and low temperature.

Kupecki carried out a stationary off-design modeling of a micro-combined heat and power unit with solid oxide fuel cells [11]. In his research, the performance maps of a mCHP system with solid oxide fuel cell were presented, in which each map is applied for evaluating electrical and overall efficiency of the system at design point and during off-design operation. This analysis shows that the electrical and overall efficiencies exceed 40% and 80%, respectively. In another research, Kupecki et al. presented a parametric evaluation of a mCHP unit with solid oxide fuel cell integrated with oxygen transport membranes [12]. Their results show that electrical efficiency of the system is in range of 23–38%, and higher auxiliary power consumption is required comparing with a conventional micro-CHP system without oxy-combustion.

Arsalis et al. presented modeling and optimization of a 1 kW HT-PEM fuel cell based mCHP system [13]. Genetic algorithm was applied and the objective function was the net electrical efficiency of the mCHP system. Almost 41% net electrical efficiency is reported, and the cogeneration thermal efficiency and overall system efficiency are 49.7% and 91%, respectively. In another research, Arsalis investigated a 100 kW liquid-cooled HT-PEM fuel cell subsystem that is integrated with an absorption chiller subsystem [14]. The system supplied 128.2 kW and 64.5 kW cooling loads using a LiBr-water double-effect system and a water–NH_3 single-effect system, respectively, with 43.8% maximum electrical efficiency. Chen et al. studied the performance of a 5 kW PEM fuel cell based residential m-CCHP with absorption chiller [15]. They showed that the current density have an important role on the performance of the system, however, this effect is different during winter and summer seasons. The better performance of CHP system in winter is due to more energy recovery from waste heat compared to summer.

Exergoeconomic evaluation combines thermodynamic analysis with the principles of economics to provide useful information, for an energy system designer, which cannot be obtained using conventional methods of thermodynamic analysis and economic evaluation. This information is absolutely essential to design a cost-effective system [16]. Kerdan et al. presented an exergoeconomic based parametric study to examine the effects of active and passive energy retrofit strategies for design improvement of building energy systems. The results of their study show that high capital investments were needed to achieve high thermodynamic performance [17]. Khani et al. conducted energy and exergoeconomic analyses on a power/cooling cogeneration system based on a solid oxide fuel cell. They showed that the exergy efficiency of the system is 6.5% higher than that of the stand-alone SOFC. Also, they observed that the exergoeconomic factor is 27.3%, the capital cost rate is 10.63 $/h, and the exergy destruction cost rate for the overall system is 28.3 $/h [18]. Previous studies regarding exergoeconomic analysis of CHP systems do not include natural gas-based PEM fuel cell system integrated with an absorption chiller.

In this paper, the performance of a PEM fuel cell based mCHP system integrated with an absorption chiller is studied using exergoeconomic analysis for residential application. Also, a thermal energy storage tank based on phase change material (PCM) is used to supply hot water. The main objective of this study is to conduct exergy and exergoeconomic analyses on an integrated natural gas based mCHP system that is able to supply electricity, cooling and hot water for a residential unit. The effects of working temperature, pressure, and current density on the performance of the system are studied and the exergy cost of electrical power and cooling effect are evaluated.

System description

A block diagram of the mCHP system is shown in Fig. 1. The mCHP system consists of a PEM fuel cell stack, a lithium bromide absorption chiller system, a natural gas steam reformer, and a PCM storage tank. The system is designed to supply the electrical power, hot water, and cooling demands of a house, concurrently. An external reformer is considered to supply carbon monoxide-free hydrogen gas to the fuel cell in order to avoid poisoning of the anode catalyst. Natural gas (27) is supplied to the burner where the required heat for the

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