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Application of thermoelectric cooler as a power generator in waste heat recovery from a PEM fuel cell – An experimental study

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ABSTRACT

In this paper, thermoelectric waste heat recovery from a PEM fuel cell has been experimentally investigated. For this purpose, an experimental system consisting of a heat exchanger, thermoelectric modules and a heat sink was built and tested under the operating conditions of a 5 kW PEM fuel cell system. The experimental results showed that using thermoelectric coolers can be a suitable solution for recovering waste heat from a PEM fuel cell. Moreover, this study provides an empirical relation for estimation of heat recovery system voltage using outlet water temperature of the PEM fuel cell. The results also showed that the overall efficiency of the system decreases with increasing outlet water temperature, indicating that overall efficiency depends extremely on the quality of the insulation. In addition, an optimal range was proposed for external loads to achieve maximum heat recovery and power generation from thermoelectric generators.

Introduction

Energy efficiency and air pollution concerns have become more important in development of the industrial systems in recent decades. Fossil fuel-based technologies are the main sources of emissions of air pollutants, such as CO_2, CO and NO_x. Moreover, uncertainties associated with fossil fuel resources and growing oil prices have led to an increased interest in the use of alternative fuels and energy sources. Meantime, fuel cells have attracted more attention due to their low emissions and high energy efficiency [1].

A fuel cell is an electrochemical energy convertor that directly converts chemical energy stored in the hydrogen gas into DC current electricity. Electrochemical reaction occurring in the fuel cell is an exothermic reaction which produces heat in addition to electricity. Fuel cells are classified into five categories based on the electrolyte they use: Alkaline Fuel Cell (AFC), Phosphoric Acid Fuel cell (PAFC), Proton Exchange Membrane Fuel Cell (PEM FC), Molten Carbonate Fuel Cell (MCFC) and Solid Oxide Fuel Cell (SOFC). Currently, among other types of fuel cells, PEM technology has been more developed. Because of its high current density and rapid start up time, this type of Fuel cell is widely used in automotive and

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residential applications. Moreover, it can be used with portable devices such as laptops, mobile phones, etc. [2].

Electrical efficiency and operating temperature of a PEM fuel cell are about 45–50% and between 60 and 65 °C, respectively [3]. The operating temperature is an important parameter for optimal operation of the fuel cell. Increasing the operating temperature more than the optimal range, leads to a reduction in theoretical efficiency as well as the maximum cell voltage. Therefore, thermal management of a PEM fuel cell is an important aspect of its practical application. For example, a 1 kW PEM fuel cell with 50% of electrical efficiency, produces 1 kW heat which must be extracted from its stacks [4].

Today, the recycle of waste heat produced in a process is one of the main strategies to improve efficiency and saving the energy. For example, waste heat from gas engines or gas turbines can be used to produce hot water or steam which then can be used for other processes or space heating. Furthermore, the performance of fuel cells is widely accepted in residential and automotive applications where the waste heat can be used for similar applications [2,5,6]. In some types of fuel cells such as solid oxide ones, the operating temperature is high enough to use it for industrial heating or electricity generation. Granovskii et al. [7] studied the performance of two hybrid systems consisting of a gas turbine and a solid oxide fuel cell. They showed that the natural gas consumption of the whole system reduced considerably by up to 20%. In another study, Gigliucci et al. [8] has experimentally demonstrated a residential CHP system based on PEM fuel cells. Their results indicate that the primary energy consumption in a CHP system compared to that of separate generation of electricity and heat, reduced by up to 10%. Shabani and Andrews [9] have experimentally studied a CHP system based on PEM fuel cells in solar-hydrogen power supply systems in remote areas. They studied the performance of a 500 W PEM fuel cell CHP system and concluded that the overall system efficiency increased by up to 72%, compared to 35–50% seen on power mode only. Another study was conducted by Hwang at al. [10] in the field of heat recovery from a fuel cell by means of a heat recovery unit. They showed that the overall system efficiency is 82% based on the lower heating value of hydrogen.

In recent years, advancements in semi-conducting materials have led to the extensive use of thermoelectric modules in waste heat recovery. Thermoelectric modules can convert a temperature difference to the DC electricity and vice versa. Thermoelectric modules are classified into two categories; thermoelectric coolers (TECs), and thermoelectric generators (TEGs). Thermoelectric modules are highly reliable small size units without any moving parts. Moreover, they are environment friendly, modular and have very long life times. The best advantage of TEGs is their ability to convert low amounts of heat into electricity. In fact, the most appropriate choice for heat recovery when waste heat is not high enough to run a heat engine, is to use TEGs [11,12].

Several studies have been done on the recovery of waste heat by thermoelectric generators. He et al. [13] used an analytical model to simulate the behavior of a solar heat pipe thermoelectric generator in different operational conditions. They reported 3.346% conversion efficiency for 1000 W m^2 solar radiation. Hsu et al. [14] used 24 thermoelectric generators (TEG) to convert heat from the exhaust pipe of an automobile to electrical energy. Love et al. [15] conducted an experimental procedure to improve the performance of thermoelectric heat recovery systems for automotive application. They reported for higher exhaust gas flowrates, thermoelectric power output increases from 2 to 3.8 W while overall system efficiency decreases from 0.95% to 0.6%. Sandu et al. [16] conducted an experimental study on heat recovery from the exhaust gas of a diesel engine using thermoelectric generators. Montecucco and Knox [17] proposed a computer model to accurately simulate the thermal and electrical dynamics of a real thermoelectric (TE) power generating system. Wang et al. [18] used a combination of 16 TEG with a plate heat exchanger to produce electrical power from low grade waste heat. They reported 83.56% heat exchanger efficiency with 108.1 mV electrical voltage achievement. Yu et al. [20,21] proposed a numerical model to study on the behavior of a thermoelectric generator based on vehicle exhaust waste heat recovery system. Aranguren et al. [19] produces 21.56 W of net power from exhaust gas of a combustion chamber using thermometric generators.

Thermoelectric modules have been also used for thermal management of fuel cells. Paris and Jones [22] developed a model for thermal management of a fuel cell by thermoelectric coolers. They showed that internal liquid cooling or external humidification of the feed gases can be replaced by thermoelectric coolers. Min Chen et al. [23] used a 3D CFD model to simulate the performance of each thermoelectric module used for heat recovery from 1 kW PEM-fuel cell. Chen et al. [24] investigated the performance of a hybrid system which consisted of a solid oxide fuel cell as well as a thermoelectric generator. They presented a correlation between current density of the fuel cell and non-dimension current of thermoelectric modules.

Rosendahl et al. [25] studied a hybrid system including a solid oxide fuel cell and thermoelectric modules. They showed that the output power of hybrid system increases up to 1085 W compared to 945 W without thermoelectric modules. Chen et al. [26] studied a new model of a hybrid system consisting of a PEM fuel cell, a regenerator and thermoelectric modules. They evaluated its main parameters and presented a correlation between density of fuel cell and non-dimension current of thermoelectric generators. Gao et al. [27] investigated the usage of thermoelectric modules to overcome the start-up problem and control of heat flux in methanol reformers at high temperature PEM fuel cells. In another study [28], they presented a numerical model of thermoelectric generators with a compact plate-finned heat exchanger for exhaust heat recovery from a high-temperature PEM fuel cell. In 2014 [29], they extended their researches to optimize the system through simulations, which leads to increase the subsystem power output by 12.9%. Hwang et al. [30] constructed a MATLAB/Simulink model to analyzed the performance of a fuel cell thermoelectric cogeneration system fed by a methanol steam reformer. They showed that the proposed thermoelectric cogeneration system can reach to a thermal combined heat and power efficiency of 80.6%. Yang et al. [31] used a multicouple TEG to recover waste heat released in an alkaline fuel. They derived analytical expressions of the performance parameters for the hybrid system. They reported that the performance of the fuel-cell can be effectively improved by