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Combined thermal characteristics analysis of steam reforming and combustion for 5 kW domestic PEMFC system

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ABSTRACT

A natural gas-based steam reformer for a domestic polymer electrolyte membrane fuel cell (PEMFC) system is thermodynamically analyzed with a special focus on the heat supply mechanism, which is critical to the endothermic steam reforming process. The interdependence of the reforming and combustion processes is evaluated through a characteristic study of heat transfer from the heat source to the reforming zone. Premixed combustion patterns may be affected by the inclusion of controlling means such as a metal fiber screen or burner placement. In this study, we attempted to enhance reforming performances of a reformer embedded in a 5 kW in-house PEMFC through modification of the combustion pattern by varying the type and placement of the burner and other operating conditions. Reforming input conditions such as steam-carbon ratio (SCR) and fuel distribution ratio (FDR) are also analyzed to quantify the overall performance such as thermal efficiency and fuel conversion rate. In our experiments involving three types of combustors—cylindrical metal fiber burner, flat type metal fiber burner and nozzle-mixing burner—the operating conditions are set so that the SCR and FDR are in the range 3.0–4.0 and 0.4–0.7, respectively. It is found that the cylindrical metal fiber burner at an appropriate location could improve thermal efficiency up to 79% by 10%, compared to other devices. This maximum thermal efficiency output is obtained with 0.63 FDR, which eventually yields 99% hydrogen conversion rate when using a cylindrical metal fiber burner, while the other burners produce 95% conversion. These outputs substantiate that the overall efficiency is strongly affected by an appropriate control for uniform temperature distribution on the catalyst layer.

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Nomenclature

PEMFC	Polymer Electrolyte Membrane Fuel Cell
SR	Steam Reforming
HTS	High Temperature Shift
LTS	Low Temperature Shift
SCR	Steam to Carbon Ratio
A/F	Air-Fuel Ratio
Fi	Molar Flow Rate of Species i
LHVi	Low Heating Value of Species i
ni	Mole of Species i
η	Thermal Efficiency

Introduction

Many countries have derived their own renewable energy projects related to residential construction. The Korean government provides financial and technical support to achieve a governmental goal to provide one million renewable energy residences by 2020. In the United Kingdom, all newly constructed residences should follow the policy of carbon dioxide reduction from 2016. Japan is implementing renewable energy policy to reduce greenhouse gases by 60–80% by 2050. In the USA, numerous programs associated with zero energy building concepts, such as LEED (Leadership in Energy and Environmental Design), are proposed for public and private organizations [1]. However, one of the most useful renewable energy resources suited for the residential buildings would be a fuel cell system that could provide not only electricity, but also heat in the form of high-temperature water, which is necessary for residential heating/cooling systems [2]. In fact, there are many residential buildings in Korea that can take advantage of the fuel cell system since natural gas supply pipelines are finely arrayed in all the cities. The operation of the fuel cell system requires a reliable supply channel of hydrogen rich gas to fuel cell stacks. In this sense, reforming means utilizing the natural gas supply network is highly beneficial for the fuel cell systems in urban areas [3]. There are many reforming techniques such as steam reforming, autothermal reforming, and partial oxidation reforming. Among these, steam reforming—which can provide the highest hydrogen yield—has been practically applied for integrated fuel cell operation.

The overall efficiency of the fuel cell system is predominantly affected by the performance of the steam reformer. The performance of the fuel cell system is greatly determined by both electrical and thermal energy conversion processes. While the stack is a major component associated with electrochemical conversion from hydrogen to electrical energy, the reformer is integral part where high temperature heat and mass transfers take place [4]. Within the catalyst cells embedded in the reformer, endothermic chemical reactions absorb massive amount of heat which is released from the high temperature combustor. However, it is unavoidable to emit enormous amount of heat from the reformer to the surroundings unless heat transfer mechanism is carefully contrived. It is highly important to study the reforming performance, which in turn greatly enhances the overall efficiency of the fuel cell system [5]. Though the abandoned heat from the device could be utilized as hot water boiling, indoor air heating, and thermal dehydration with the purpose of overall efficiency improvement, primary research topics should cover, in advance, major causes that straightforwardly impact the performance of the reforming process, such as catalyst activity, heat source/transfer analysis, accommodation of various fuels, and thermo-structural analysis.

Concerning the catalyst activity in steam reformer, many studies have been extensively conducted that could enhance reforming efficiencies: synthesizing different kinds of catalysts under various reactions for effective steam reforming process, analyzing the activity with an optimal catalyst composition, and developing various kinetics models for various mass and heat transfer processes, etc. [6–11]. The degradation and durability of catalyst in reforming reaction were also investigated [12]: hydrocarbon fuels under normal operating conditions may cause adverse effects on catalysts such as coking, sintering, and sulfur poisoning. Though these research outputs could disclose fundamentally related physics, it does lack provide thermal information that strongly affect favorable or adverse catalyst characteristics. It should be noted that heat transfer mechanism to catalyst is much more important factor than the catalyst reaction activity itself on macroscopic scale [13].

Effectiveness of heat managements have been studied using various heat sources such as catalytic combustion, flame combustion, and electric furnaces. In order to utilize the unused energy of the anode off-gas for heating and reforming, Lee et al. investigated the operating characteristics of a steam reformer with planar heat exchanger and catalytic combustor [15]. Zanfir et al. presented a theoretical study of methane steam reforming coupled with methane catalytic combustion in a catalytic plate reactor based on a two-dimensional model [14]. Jin et al. studied microchannel reactors assembled with combustion and reforming reaction blocks to enhance the heat transfer rate and long term stability [13]. Mohammad et al. attempted to improve the steam reforming process using CLC technology, investigating important parameters such as temperature, mole fraction, and gas conversion [16]. Lee et al. investigated the maximum methane conversion and hydrogen production rates (94.7% conversion rate at a temperature of 650 °C and GHSV of 10000 h^{-1}) compared to the equilibrium values [17]. As shown in the above studies, the reforming efficiency could be noticeably improved by various factors such as heat source dependence, heat transfer control on empirical geometric design, fuel type, and calorie distribution. However, these mainly focus on the combustion process with one parameter analysis, leading to the neglect of mutual interdependence of combustion and reforming reaction processes.

To thoroughly understand the reforming mechanism, our study analyzed heat transfer characteristics from heat source to reforming catalyst layer which disclose the correlation between reforming and combustion. The goal of our study is to enhance system performance of a reformer embedded in a 5 kW in-house PEMFC through trying various combustion patterns with variations of burner type and placement, and operating conditions. From the baseline nozzle-mixing burner, it is sought to improve reforming performances using other metal fiber burners (cylinder and flat type screen) and also testing various operating conditions such as fuel