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Energy performance and CO_2 emissions of fuel cells for residential application in Chinese hot summer and cold winter areas

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Abstract. The energy consumed in residential buildings has become a key factor in China. An energy-efficient and low-emission fuel cell co-generation system (FC-CGS) is a promising electric and thermal energy generation technology to enhance the energy-saving effects for residential application. SOFC-CGSs and PEFC-CGSs are the two major types of residential FC-CGSs. This paper aims to analyze the energy-saving effects of FC-CGSs for residential buildings in Chinese hot summer and cold winter areas. Changsha city is selected as an example. This study at first outlines SOFC-CGSs and PEFC-CGSs, introduces the simulation methods and develops a standard family model for simulation, then calculates domestic demands of the system, and finally compares the primary energy consumption and CO_2 emissions of FC-CGSs with those of a traditional power and heat generation system based on gas and electricity. The results show that residential PEFC-CGSs offered primary energy reduction of 8.8% in winter. However, the average reductions of primary energy and CO_2 emissions of SOFC-CGSs were 15.1% and 9.9%, respectively.

1. Introduction

Nowadays, environmental deterioration and climate change due to the greenhouse gas (GHG) emissions threaten human health and quality of life, and even influence the development of economy and society. Primary energy consumption is a main cause of GHG emissions. As a large part of total energy consumption of China, the energy consumed in residential buildings has become a key factor affecting economic development[1]. It is important to reduce energy demands and boost energy efficiency of residential buildings in China.

In China, the utilization efficiency of primary energy in conventional power generation is only 36%. Large thermal energy is wasted in terms of power transmission and generation processes. Other than the power plant, the residential fuel cell co-generation system (FC-CGS), which can convert the hydrogen energy recovered from a single fuel source (ex. natural gas) into electricity and heat directly, is a good option to enhance the energy-saving effects for residential buildings. The utilization efficiency of primary energy of residential FC-CGSs can reach approximately 80% including power and heat. It was reported by measurements that FC-CGSs could save averagely annual primary energy demand by 6% and CO_2 emission by 11% respectively for residential buildings[2].

A series of studies have investigated the energy and environmental performance of residential FC-CGSs. Kazunori and his team analyzed the primary energy performance, CO_2 emissions and peak electric load for a house with residential FC-CGS in Austin[3]. They showed that the use of residential fuel cells could offer environmental benefits from reducing primary energy consumption and CO_2 emissions, and grid reliability benefits by reducing peak electric load. T Wakui et al.[4] conducted the study on how to increase the operating factor of FC-CGS with minimum output. After that, he and his team studied CO_2 mitigation, and reduction of primary energy consumption of the systems contributed by residential FC-CGS in Japan[5]. In our previous studies, the authors discussed the energy performance of residential FC-CGSs in Chinese cold climate areas, and showed a good potential application of FC-CGSs in Chinese hot summer and cold winter areas[6-7]. However, application of residential FC-CGSs especially reduction of CO_2 emissions is still a futuristic concept in China.
Therefore, in order to study the energy-saving performance and CO_2 emissions of residential FC-CGSs for Chinese hot summer and cold winter areas, this paper introduces the simulation method of two major kinds of residential FC-CGSs, then evaluates the primary energy demand of these systems, analyzes CO_2 emissions reduction, and finally compares them with traditional power and heat generation system. Changsha city is selected as an example.

2. Methodology

2.1. Analysis of residential FC-CGSs
Polymer electrolyte fuel cell co-generation systems (PEFC-CGSs) and solid-oxide fuel cell co-generation systems (SOFC-CGSs) are two major kinds of FC-CGSs for residential application. PEFC-CGS is operated at relatively low temperatures around 90°C with a fast activation time, and reaches a high exhaust heat recovery efficiency of 45.0%. SOFC-CGS has a high activation and electricity generating efficiency and can generate high temperature of recovery heat. PEFC-CGS was available in Japanese market, however, SOFC-CGS is likely to be commercialized in the near future.

Residential FC-CGS is consisted of a fuel cell (FC) unit and a hot water tank unit. The FC unit can generate power and recover exhaust heat. Exhaust heat from the FC unit is recovered in the form of hot water and then stored in the hot water tank. Table 1 indicates the Schematic illustration and the basic specification of residential PEFC-CGS and SOFC-CGS for simulation in this paper. In this investigation, Daily Start & Stop (DSS) operation of the PEFC unit, which means that activation/stop time was designated beforehand based on the past load data, was set up in the PEFC simulation as an optimal operation method for energy-saving. When the PEFC unit was stopped, the standby power requirement was set to 20W. Apart from PEFC, SOFC was operated from a very high temperature at above 800°C, which caused a long time for start or stop. Thus, SOFC should be operated for 24 hours. After operation of SOFC-CGS, surplus hot water would be wasted at a radiator when the storage tank was full. On the side of the output control method, operation to just follow power load was chosen to prevent surplus power generation for both two residential FC-CGSs. On the side of hot water supply, tap water was set up to heat up to 60°C for PEFC and to 70°C for SOFC by using recovered exhaust heat. Also, 40°C hot water was provided for domestic demands by mixing the stored hot water and the tap water.

Table 1. Schematic illustration and specification of residential FC-CGSs

Specification items	PEFC-CGS	SOFC-CGS
Power generation efficiency	33%	41.5%
Exhaust heat recovery efficiency	45%	35.4%

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Ratio of heat recovery to power generation	1.36	1.27
Rated power output	1 kW	0.7 kW
Rated exhaust heat output	1.36 kW	0.89 kW
Temperature of hot water stored in tank	60 °C	70 °C
Capacity of hot water tank	200 liter	90 liter
Activation temperature of fuel cell unit	60- 100 °C	700- 1000 °C
Fuel resource	Natural gas	Natural gas

2.2. Building data and input loads

A standard building model situated at Changsha is considered for simulation. It has total of energy reference floor area (57.83 m^2) including the four rooms: the main bedroom (12.87 m^2), the bedroom 1 (9.9 m^2), the bedroom 2 (12.87 m^2), and the living room (22.19 m^2), which are all air-conditioned rooms for heating or cooling. Physical characteristics of the simulation building model are decided according to the Chinese design standard for energy efficiency of residential buildings in hot summer and cold winter zone (JGJ75-2012), as shown in Table 2. The standard family was assumed to be dual-earner parents and two children. Table 3 shows the details of utilized appliances for each room in the simulation.

Table 2. Physical characteristics of the simulation building model.

Component	Physical characteristics (from indoor to outdoor) (mm)
wall	Stucco 50, reinforce concrete 200, expanded polystyrene 20, stucco 50
Roof	Stucco 50, reinforce concrete 150, expanded polystyrene 30, stucco 50
Glazing	Single glazing
Sunroom	0
Overhang	0
Ground	Expanded polystyrene 50, reinforce concrete 1000

Table 3. Description of each room in the simulation building

Room	Area (m^2)	User	Appliance
Main bedroom	12.87	Parents	Air conditioning; Lamp
Bedroom 1	9.9	Son	Air conditioning; Lamp
Bedroom 2	12.87	Daughter	Air conditioning; Lamp
Living room	22.19	Family	Air conditioning; Television; Computer; Dish rag; Lamp
Wash room	7.29	Family	Washing machine; Lamp
Kitchen	8.91	Family	Refrigerator; Electric pot; Kettle pot; Electric cooker; Gas oven; Lamp
Vestibule	3.47	Family	Lamp

The input load data at 1-minute intervals of the FC-CGSs simulation programs[8] includes occupant-related electricity, the domestic hot water demand and thermal load by air-conditioning for the winter calculation period (from December 1st to next February 28th). Initially, the occupant-related electricity and the volumes of domestic hot water demand could be directly calculated by the appliance utilization in Table 2 and the measurements on Chinese energy consumption[9]. Secondly, domestic hot water energy consumption was counted by the Equation of Specific Heat Capacity, in which the water temperature difference equals the required hot water supply temperature at 40 °C minus the tap water temperature. Furthermore, the space thermal load was calculated by the dynamic simulation program DesignBuilder. The internal heat (human body, electric appliances, etc.) was considered here. Air conditioning controlled the indoor temperature above 18 °C in winter when people is indoor. Indoor relative humidity was controlled at the high peak 60% and the low peak 40%. Ventilation change rate was 0.5 h^{-1}. Finally, input load data by power and heat (at one-minute intervals) was created based on obtained data for calculating period of winter. The results of input load data for the simulation are illustrated in figure 1.

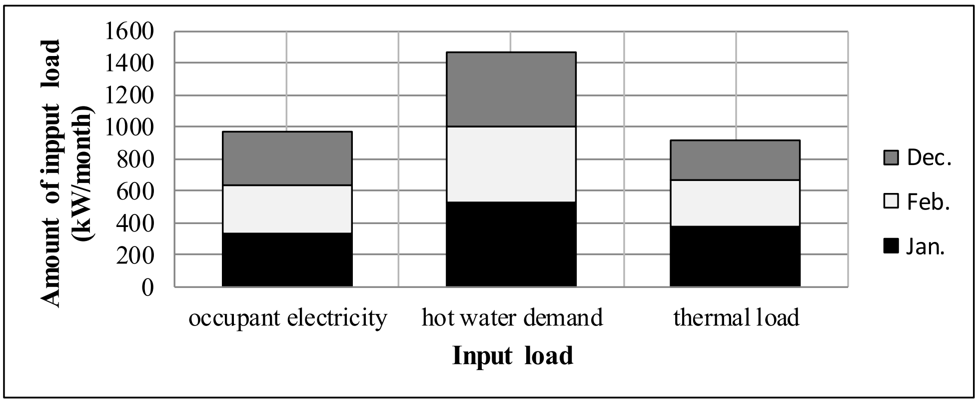


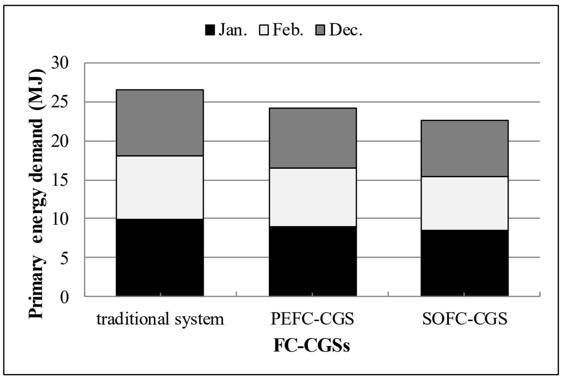
Figure 1. Monthly domestic energy demands for simulation model

3. Results and discussion

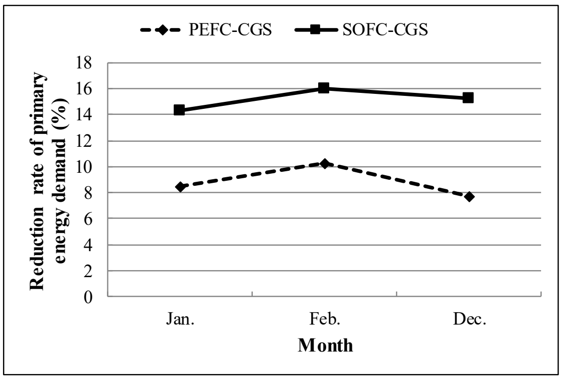
3.1. Primary energy demand and reduction rate

The primary energy demand is the significant indicator on energy performance of FC-CGSs. The output data of the FC-CGSs simulation programs is energy demand of electricity and natural gas bought from the company, which can be converted to primary energy by conversion factors. The values of 10 MJ/kWh, and 45.9 MJ/Nm^3 are the conversion factors of grid electricity demand and natural gas demand, respectively, to primary energy demand in China. Figure 2(a) shows that the primary energy demand of PEFC-CGS utilization is 9.0 MJ, 7.4 MJ and 7.8 MJ in January, February and December, respectively. While SOFC-CGS consumed 8.5 MJ, 6.9 MJ and 7.2 MJ in January, February and December, respectively.

In order to contrast further the energy-saving performance of SOFC-CGS and PEFC-CGS, the reduction rate of primary energy demand is calculated, which is identified to be compared between FC-CGS and the traditional system. PEFC and SOFC offered average reductions at 8.8% and 15.1% respectively of primary energy demand in winter, as shown in figure 2(b). It claims that the SOFC-CGS is a good energy efficiency system for residential applications in Chinese hot summer and cold winter areas.



(a)



(b)

Figure 2. Monthly primary energy demand and reduction rate of monthly primary energy demand

3.2. CO_2 emissions and reduction rate

Primary energy consumption is a main cause of CO_2 emissions. Electricity and natural gas bought from the company can be converted to CO_2 emissions by conversion factors. The values of 0.69 kg-CO_2/kWh, and 2.1 kg-CO_2/kWh are the conversion factors of grid electricity demand and natural gas demand, respectively, to CO_2 emissions[10]. Figure 3 shows that the monthly CO_2 emissions of FC-CGSs are lower than that of the conventional system without a FC unit. Residential PEFC-CGS and SOFC-CGS offer reductions in CO_2 emissions in winter. Residential buildings integrated PEFC-CGS could reduce CO_2 emissions by 6.9%, while the SOFC-CGS utilization could decrease CO_2 emissions by 9.9% in Changsha city.

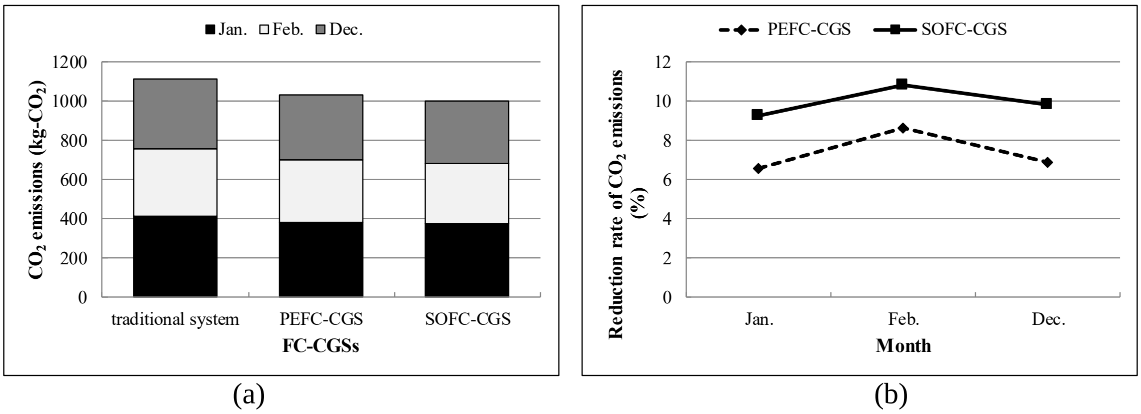


Figure 3. Monthly CO_2 emissions and reduction rate of monthly CO_2 emissions

4. Conclusion

This paper shows the possibility to further reduce primary energy of residential building by active technologies such as residential FC-CGSs. This study aims to analyse the energy-saving performance; in terms of primary energy demand and CO_2 emissions, and their reduction rates; of PEFC and SOFC installed in residential buildings in Chinese hot summer and cold winter areas.

SOFC-CGSs are effective in reducing primary energy demand and CO_2 emissions in winter. Compared with conventional power and heat generation systems, the study of SOFC-CGSs achieve average reduction of 15.1% in primary energy demand and 9.9% in CO_2 emissions for the selected Chinese city Changsha. PEFC-CGSs are also recommended to utilize for residential application in winter, because of their low operation temperature. PEFC-CGSs could reduce the monthly primary energy demand at least by 7.7% and average at 8.8% in winter in Chinese hot summer and cold winter areas.

Acknowledgements

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