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Performance study of a dual power source residential CCHP system based on PEMFC and PTSC

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ABSTRACT

This paper presents an innovative, hybrid residential CCHP system based on fuel cell and solar technologies that can provide electric power, heating and cooling. The CCHP system consists of a proton exchange membrane fuel cell (PEMFC) stack, parabolic trough solar collector (PTSC), double-effect absorption chiller and their relevant accessories. The effects of key operating parameters for PEMFC and PTSC systems (e.g.: current density, operating temperature and solar radiation) on the system thermodynamic performance are analyzed and discussed. The results show that the PEMFC operation temperature has a significant influence on the PTSC output performance in a hybrid CCHP system and that the PTSC also plays an important role as a bridge between the PEMFC stack and absorption chiller. The maximum efficiency of a hybrid system can reach 80.5%, which is higher than conventional CCHP systems, due to the high efficiency of PEMFC, PTSC and double-effect absorption chiller. The economic and environmental analysis of CCHP system are also performed, the results indicate the project is practicable, meanwhile, high current density and solar radiation and low operating temperature can improve pollutant emissions reduction of the system.

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1. Introduction

In China, due to the tremendous growth in energy consumption and environmental pollution, renewable alternative energy and efficient power systems have received much attention from the government and researchers. Combined cooling heating and power systems (CCHPs) with high efficiency and low pollutant emissions are promising technologies to fix these problems. They can provide sufficient energy to meet the demand of industrial, commercial and residential applications with a low primary energy consumption rate and carbon dioxide emissions. A CCHP system using renewable energy can be classified based on the prime mover (e.g., fuel cells, solar collectors, biomass boilers, wind power stations). Particularly, due to their small size, low noise and cost, fuel cells and solar collectors are the most popular and appropriate prime movers applied in residential CCHP systems.

Fuel cells are probably one of the most promising high efficiency power source technologies due to their high electric efficiency, low emission and short start-up time [1–3]. Particularly, PEMFC and solid oxide fuel cell (SOFC) technologies are widely used for CCHP systems. Some of the relevant studies that have been performed are as follows: Yu et al. [4] designed a SOFC based CCHP system combining a double-effect absorption chiller and analyzed the effects of current density and fuel utilization on system performance. Liu and Leong [5] developed a CCP system consisting of a SOFC and absorption chiller. The waste gas from the SOFC was combusted to provide heat to the absorption chiller. A key parametric analysis was conducted, and the results showed that the system efficiency can reach 77%. Ma et al. [6] designed a new CCHP system based on the combination of a SOFC and gas turbine (GT), using an ammonia-water mixture to recover heat from the SOFC–GT. The overall system efficiency could reach 80%. Compared to SOFCs, PEMFCs have a higher efficiency, lower noise, shorter start-up time and are becoming more popular for residential, micro-CCHP systems [7]. Chen et al. [8] proposed a 5 kW PEMFC-based residential micro-CCHP with a single absorption chiller. The effects of the operating parameters (e.g., inlet gas temperature and pressure, fuel cell operating temperature and current density) on system performance were studied, it was found that the system efficiency in summer mode is 70.1%. Vadiee et al. [9]

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Nomenclature

A	area, cm^{-2}
c	specific heat capacity, $kJ\ kg^{-1}\ K^{-1}$
C	concentration, $mol\ cm^{-2}$
D	diameter or vapor generating rate, m or $kg\ s^{-1}$
f	mole flow rate, $mol\ s^{-1}$
F'	collector efficient factor
F_R	heat removal factor
h	mass specific enthalpy or radiation heat coefficient, $kJ\ kg^{-1}$
I	current, A
J	current density, $A\ cm^{-2}$
$\dot{m}$	mass flow rate, $kg\ s^{-1}$
n	number of equivalents involved in reaction
N	number of single cell
p	pressure, atm
P	power, kW
r	resistivity, Ω cm
R	resistance or gas constant, Ω or 8.3143 $J\ mol^{-1}\ K^{-1}$
S	stoichiometry or absorbed solar radiation, $W\ m^{-2}$
T	operating temperature of fuel cell, K
U_L	overall solar collector heat loss coefficient
U_o	overall heat transfer coefficient

Greek letters

ξ	empirical coefficient for calculating activation overvoltage
λ	semi-empirical coefficient for calculating water content of PEM
μ	fuel utilization factor
η	efficiency
ε	emissivity

Subscripts

act	activation
conc	concentration
el	electric
h	high
hw	hot water
i	inlet
int	internal
l	low
M	membrane
o	outlet
ohm	ohmic
st	stack
th	thermal

investigated the feasibility of a PEMFC based CHP system that would provide power and other energy sources for a commercial greenhouse. The results indicated that a 3 kW fuel cell system is able to cover the 25% and 10% of the usual electricity and heat demands of 1000 m^2 greenhouse during a year, respectively. Aki et al. [10] developed a residential, micro-CCHP system based on PEMFCs to supply electricity and hot water to six families. The results showed that the system is able to reduce the prime energy consumption by 6% and mitigate carbon dioxide emissions by 11%. Giacppo et al. [11] investigated a 3 kW power device with two 1.5 kW PEMFC stacks for a CHP application; a maximum stack power of 2.29 kW was obtained at 105 A. Lee et al. [12] carried out an exergetic and exergoeconomic evaluation of a 100 kW-class SOFC based CHP system. The results indicated that, to improve the cost effectiveness of the whole system, the investment costs on SOFC stack, fuel blower, heat-recovery water pump and inverter should be reduced. Meanwhile, the efficiency of integrated reformer, pre-heaters should be improved. Bang-Moller and Rokni [13] conducted a modeling study on CCHPs based on biomass gasification, SOFC and micro gas turbine (MGT). The results indicated that the highest electrical power efficiency is obtained at 50.3%, when SOFC and MGT are both employed as the prime movers in system.

Moreover, as another type of green energy, solar energy is widely used in CCHP/CHP systems. A series of studies have been performed [14,15]. Kalogirous and Tripanagnostopoulos [16] designed a hybrid photovoltaic/thermal (PV/T) solar system to supply domestic hot water and electricity. The heat extracted from PV modules was translated to hot water or air to keep the PV operating at a normal level and supply domestic hot water. The results showed that sufficient electricity and heat was produced by the PV/T system, and the economic viability of the system could be improved. Al-Sulaiman [17] presented a CCHP system incorporating a PTSC, organic Rankine cycle (ORC) and single-effect absorption chiller using three operating modes: solar mode, solar and storage mode and storage mode. Depending on the solar radiation, one of the three modes is chosen to optimize the system operating conditions. The simulation results showed that the maximum system efficiency of 94% is obtained in solar mode, while 47% and 42% efficiency are obtained in the other two modes, respectively. Bouvier et al. [18] conducted an experimental analysis of a solar parabolic trough collector used in a micro-CHP system. The PTSC directly generated steam with a 40% efficiency, and a parametric study of the system was performed. The simulation results indicated that a system based on a PTSC and steam engine can produce 18.3 kW of thermal power and 1.4 kW of electric power. Wang et al. [19] performed an experimental investigation of a dual source absorption chiller (AC) based on waste heat from an internal combustion engine (ICE) and solar energy. The refrigeration performances of the mixed effect AC in both waste heat mode and solar mode were tested and discussed. Sanaye and Sarrafi [20] optimized a CCHP system equipped with a conventional photovoltaic (PV) system, concentrated photovoltaic/thermal (CPVT) system, and evacuated tube (ET) collector. The performances of the various types of power device combinations were compared, and the optimal combination was obtained to keep the system operating at the highest relative net annual benefit (RNAB) and exergy efficiency. Wang et al. [21] proposed a building cooling heating power systems based on a flat-plate solar collector, and performed a parametric optimization using a genetic algorithm. The results showed that the optimal system efficiencies in CHP mode, CCP mode and power mode are 19.10%, 27.24% and 10.47%, respectively. Shah et al. [22] developed an off-grid hybrid distributed energy system incorporating PV, battery and CHP to fulfill the residential load demand. The simulations on system technical viability at different areas of U.S. were conducted, and the results showed that the system can meet the electrical load demands throughout the U.S. using reasonable sized components. Abdelhady et al. [23] presented a co-generation plant based on PTSC, which can produce 6 MW of electric power and 21.5 MW of heat power. The simulation results showed that the levelized cost of electricity of the system is estimated to be 1.25 USD/kW h, and that the green house gas (GHG) emissions are about 7300 toe/year. Boyaghchi and Heidarnejad [24] proposed a micro solar CCHP system integrated with ORC for summer and winter season. The system optimization was conducted using Genetic Algorithm (GA),

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