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Thermodynamic performance analysis of a fuel cell trigeneration system integrated with solar-assisted methanol reforming

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ABSTRACT

A solar-assisted trigeneration system for producing electricity, cooling, and heating simultaneously is an alternative scheme to improve energy efficiency and boost renewable energy. This paper proposes a phosphoric acid fuel cell trigeneration system integrated with methanol and steam reforming assisted by solar thermal energy. The trigeneration system consists of a solar heat collection subsystem, methanol steam reforming subsystem, fuel cell power generation subsystem, and recovered heat utilization subsystem. Their respective thermodynamic models are constructed to simulate the system input/output characteristics, and energy and exergy efficiencies are employed to evaluate the system thermodynamic performances. The contribution of solar energy to the system is analyzed using solar energy/exergy share. Through the simulation and analysis of methanol and steam reforming reactions, the optimal reaction pressure, temperature, and methanol to water ratio are obtained to improve the flow rate and content of produced hydrogen. The thermodynamic simulations of the trigeneration system show that the system energy efficiencies at the summer and winter design work conditions are 73.7% and 51.7%, while its exergy efficiencies are 18.8% and 26.1%, respectively. When the solar radiation intensity is different from the design work condition, the total energy and exergy efficiencies in winter decrease approximately by 4.7% and 2.2%, respectively, due to the decrease in solar heat collection efficiency. This proposed novel trigeneration system complemented by solar heat energy and methanol chemical energy is favorable for improving the energy level of low-temperature solar energy and promoting the application of renewable energy.

1. Introduction

A trigeneration system for simultaneous production of cooling, heating, and power is based on energy cascade utilization, and it can improve energy utilization efficiency [1]. At the same time, a trigeneration system has various technical, environmental, and socio-economic benefits on different levels, such as reducing operation costs, improving energy supply reliability, and reducing greenhouse gas emissions [2]. Currently, more renewable energy technologies are being introduced into trigeneration systems to boost renewable energy applications, decrease traditional fossil fuel consumption, and mitigate negative environmental impacts. More and more integrated trigeneration systems with different structures and functions have been proposed and developed [3]. Theses novel integrated trigeneration systems have been studied from system configuration and optimization, thermodynamic performance, operation strategy, and economic analysis, etc. For example, Wang et al. [4] optimized the capacity configuration of a solar-assisted trigeneration system integrated organic Rankine cycle (ORC) with an ejector refrigeration cycle. Gholamian et al. [5] designed a trigeneration system based on biomass gasifier and solid oxide fuel cell (SOFC), and the maximum exergy efficiency is 37.92% with a CO_2 emission of 20.37 t/MW h which shows an increase of 49.88% in exergy efficiency and 64.02% decrease in CO_2 emission compared to the solo SOFC system. Wang and Yang [6] proposed a hybrid electric-thermal (HET) following operation strategy for a ploygeneration system driven by solar energy and natural gas to focus on the supply matching of domestic hot water, space cooling/heating and electricity and improve the operation performances. Aimed to the cost allocations of multi-products from trigeneration system, Wang and Mao [7] discussed the economic cost using the specific exergy costing approach, including electricity, water for cooling or heating, and domestic hot water. Considering renewable energy sources including solar energy, wind energy, hydropower, and geothermal, solar energy could be the best option for the future because it is the most abundant and is inexhaustible, giving solid and increasing output efficiencies compared to other sources of energy [8].

Solar energy can be significantly utilized for trigeneration, and various such technologies have been proposed. These technologies are

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Nomenclature

ORC	organic Rankine cycle
PAFC	phosphoric acid fuel cell
PAS	pressure swing adsorption
PEMFC	proton exchange membrane fuel cell
PTC	Parabolic trough collector
PV	photovoltaic
SOFC	solid oxide fuel cell

Symbol

A	collector area
c	specific heat of oil
E	electricity
Ex	exergy
f	correction factor
F	Faraday constant
G	Gibbs free energy
h	heat transfer coefficient
I	electric current
m	mass flow rate
n	molar flow
P	pressure/electric power
Q	heat energy
r	share ratio
S	entropy
SI	solar radiation intensity
T	temperature
V	volume/voltage
η	efficiency
θ	solar incident angle
μ	chemical potential

classified as design, analysis, modeling and simulation, economics, and environmental issues [9]. Ebrahimi and Keshavarz [10] introduced the solar plate collector into the basic trigeneration system to provide a portion of the thermal energy demand and optimized the optimum conditions such as azimuth angle and tilting angle for the solar collector in five different climates. The results showed that a higher energy saving ratio is achieved during the partial load operation of an engine in the solar-assisted trigeneration system. Chang et al. [11] designed an 8 kW residential trigeneration system based on a proton exchange membrane fuel cell (PEMFC) and solar energy and presented the performance analysis influenced by current density, operating temperature, solar radiation, and ambient temperature. In particular, current density, solar radiation, and ambient temperature have a significant impact on system efficiency. Soheyli et al. [12] modeled a novel trigeneration system including photovoltaic (PV) modules, wind turbines, and solid oxide fuel cells (SOFC) as the prime movers; they also employed the co-constrained multi objective particle swarm optimization algorithm to optimize the system structure and configuration in two base operation strategies. Moreover, Askari et al. [13] studied the economic effects of solar PVs, solar collectors, and fuel price on the optimization of a typical micro natural-gas trigeneration system, concluding that the application of a solar collector is economically justifiable when fuel costs increase by at least 0.3 $/m^3. Wang et al. [14] paid more attention to the environmental impacts of the trigeneration system integrating solar PV and/or heat collectors and optimized the configurations considering different operation modes to minimize the life cycle environmental impact. The results indicated that the average life cycle energy efficiency is 51.66%, in which the energy sources consist of solar energy, natural gas, diesel oil, and coal.

In these integrated trigeneration systems with solar technologies, the prime mover that transforms energy from thermal, electrical, or pressure forms to the mechanical form is the key component to determine the configuration and operation strategy. In recent years, gas engines and gas turbines are have been primarily installed as the prime movers [15]. However, taking environmental issues into consideration with respect to the design, a fuel cell is the cleanest method for producing electricity that uses hydrogen and oxygen to generate electricity, with byproduct water as the only output. Additionally, the fuel cell system has a higher reliability due to few moving components [15]. Using hydrogen as fuel for a fuel cell is a type of clean energy, and it plays an important role in the energy supply sector.

The main methods of solar-based hydrogen production includes photovoltaic, photo-electrolysis, bio-photolysis, and solar thermal energy [16]. First, for the photovoltaic method, solar energy is converted into electricity by the PV cells, and then hydrogen is produced from the electrolysis of water using electricity. The total efficiency of converting solar energy to chemical hydrogen energy is approximately 16% [17]. Second, photo-electrolysis uses photoelectrochemical light collecting systems to directly decompose water into hydrogen and oxygen. However, this technology suffers from material problems such as low transfer efficiency, low lifetime, and high land space and semiconductor requirements [17]. Third, bio-photolysis is the decomposition of water into hydrogen and oxygen molecules using solar energy under anaerobic conditions carried out by microalgae and cyanobacteria [16]. In bio-photolysis, microalgae emit solar energy to generate electrons, which are mediated by ferredoxin, and the electrons are accepted by the hydrogenase enzyme to produce hydrogen. Currently, bio-photolysis hydrogen production is in the early development stage of laboratory-scale testing or small scale outdoor demonstration projects. Of the above three solar hydrogen production methods, water electrolysis using photovoltaic modules is the most mature. This method, however, transfers solar energy to electricity and then continues to transfer electrical energy to hydrogen chemical energy. For the electricity output from the trigeneration system, this method is not reasonable for transferring hydrogen energy to electricity using a fuel cell again. It is inferior to the method of transferring solar energy to electricity for users directly adopting PV technology. Finally, the hydrogen production from solar thermal energy and thermochemical processes is an alternative technological approach to the fuel cell trigeneration system. Thermochemical methods utilize concentrated solar radiation as a high temperature heat source to achieve the endothermic reaction, and they are classified to direct thermolysis of water, thermochemical cycles and cracking, reforming, and gasification of hydrocarbons. In these methods, water thermolysis requires a high-temperature heat source above 2500 K, while the latter two methods allow for the possibility of operating at lower temperatures.

Compared to these solar-powered hydrogen production technologies, hydrogen production through the reforming of hydrocarbons using low-temperature solar thermochemical processes is adopted and integrated into the novel fuel cell trigeneration system described in this paper. Thus, the originality of this work lies in proposing a novel fuel cell trigeneration system integrating solar-assisted methanol reforming and analyzing the system thermodynamic performances of design and off-design work conditions on the basis of the optimization of methanol and steam reforming. Section 2 proposes the novel trigeneration system and presents the evaluation criteria, Section 3 presents the thermodynamic performances of design and off-design work conditions, and Section 4 summarizes some conclusions.