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Performance analysis of a photovoltaic-thermochemical hybrid system prototype

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HIGHLIGHTS

- A modular photovoltaic-thermochemical hybrid system prototype is proposed.
- Net solar-electric efficiency up to 41% is achievable.
- Stable solar power supply is achievable via convenient energy storage.
- The modular design facilitates the scalability of the hybrid system.

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ABSTRACT

A solar photovoltaic (PV) thermochemical hybrid system consisting of a point-focus Fresnel concentrator, a PV cell and a methanol thermochemical reactor is proposed. In particular, a reactor capable of operating under high solar concentration is designed, manufactured and tested. Studies on both kinetic and thermodynamic characteristics of the reactor and the system are performed. Analysis of numerical and experimental results shows that with cascaded solar energy utilization and synergy among different forms of energy, the hybrid system has the advantages of high net solar-electric efficiency (up to 41%), stable solar energy power supply, solar energy storage (via syngas) and flexibility in application scale. The hybrid system proposed in this work provides a potential solution to some key challenges of current solar energy utilization technologies.

1. Introduction

As one of the few potential solutions to global energy and environmental problems, solar energy technologies are widely employed to supply heat [1], generate electricity [2] and produce solar fuels [3]. This is achieved separately or simultaneously by different solar energy technologies, such as solar photovoltaic (PV), thermal and photocatalytic [4] conversion approaches. Comprehensive utilization of solar energy by combining the strengths of multiple solar conversion approaches could enhance efficiency and reduce cost. It has become an intensively studied area of solar energy research in recent years. A typical example is the PV-thermal (PVT) technique, which aims at recovering and utilizing thermal energy released from PV generation using a complementary thermal module. The PVT technique was first proposed by Wolf [5] in the 1970s. Since then, many studies on PVT systems have been performed [6], most of which focused on heating and cooling by the waste heat from PV cells. Performances of such systems have been studied theoretically and experimentally from thermodynamic [7], economic [8] and environmental [9] perspectives, and higher efficiency, better economy and lower emissions of greenhouse gases have been achieved.

PVT systems aiming at direct utilization of thermal energy are severely constrained in space and time owing to challenges in thermal energy transport. Additionally, despite impressive first-law-based total efficiencies of up to 80% [10], increasing the electricity ratio among the total energy output remains a considerable challenge, which, to a large extent, pivots on how thermal energy can be efficiently converted to power. A few research groups have attempted to address this issue by using organic Rankin cycle (ORC) or a thermoelectric generator (TEG) thermal module to

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generate electricity from the waste heat of PV cells [11–14]. However, owing to opposite trends in the responses to the temperature of the PV part [15] and the thermal part, as well as their low heat-electricity conversion efficiencies, many (if not all) of the gains that the thermal parts bring about are cancelled to a large extent. Besides, difficulties in stable power supply (resulting from space-time intermittency of solar energy) and/or scale-matching remain unresolved in these systems.

To achieve the goals of high solar-electric efficiency and stable power supply, we have proposed an efficient solar power generation system that integrates a PV module and a low-temperature methanol decomposition module [16]. In the proposed system, sunlight is concentrated onto PV cells; part of the sunlight is converted to electricity directly by the PV cells and the rest is converted to heat, which is absorbed by the endothermic methanol decomposition at approximately 250 °C and stored in syngas in the form of chemical energy. The stored solar chemical energy is released in a combined cycle during combustion at approximately 1300 °C and eventually converted to electricity. During the entire process, solar energy is utilized in a cascaded way and the low-temperature (250 °C) dissipated heat from the PV cells is upgraded to high-temperature (1300 °C) heat, partially assisted by chemical energy. Thermodynamic analysis indicated that the system was characterized by high net solar-electric (NSE) efficiency (43%; higher than the 35% efficiency of the solar-methanol thermochemical power generation system [16,17]) and easy energy storage. However, the detailed matching of the PV and methanol thermochemical modules and the design of the PV hybrid reactor have not been studied.

For the methanol decomposition/reforming reactor without the PV module, Jin et al. [18] designed a 5 kW solar receiver/reactor prototype for solar methanol decomposition; the conversion ratio of solar thermal energy to chemical energy was in the range of 30%–60% with a concentration ratio of 70. Based on the same reactor, Liu et al. [19] further analyzed the performance of methanol steam reforming and obtained similar results. In contrast to the relatively large scale reactor of Jin and Liu, Zimmerman et al. [20] developed a micro solar methanol reforming reactor aiming at a high collector temperature without sunlight concentration. Theoretical analysis showed that a collector temperature of up to 250 °C was achieved by employing vacuum insulation and selective absorbing coating. Gu et al. [21,22] expanded further on this concept by incorporating a compound parabolic concentrator (CPC, concentration ratio of 1.75) in the reactor and achieved a thermal efficiency of 65–71% with a solar collector temperature of 250–300 °C. All of the above methanol thermochemical reactors were designed for a relatively low concentration ratio (lower than 100).

However, the concentration ratio of a PV cell (i.e., efficient multi-junction GaAs), which can withstand temperatures higher than 200 °C [23], must be higher than 300 owing to economic considerations [24]. On account of the high energy flux resulting from this high concentration ratio, heat utilization and thermal management of PV cells become vital issues [23]. Furthermore, when the concentration ratio increases from below 100 to above 300, not only the energy flux increases, but also the type of concentrator changes from CPCs and line-focus trough concentrators to point-focus Fresnel concentrators. Thus, the geometry matching and multi-field coupling between the high-concentration PV (HCPV) cell and the methanol decomposition reactor become important issues.

In this work, we focus on the practical integration of a HCPV cell with a methanol thermochemical reactor and propose a hybrid system consisting of a point-focus Fresnel concentrator, a multi-junction PV cell and a methanol thermochemical reactor. Furthermore, we design and manufacture a modular methanol reactor suitable for HCPV cells. The performance of the reactor and the reactor-based system is analyzed, and implications for efficient utilization of solar energy are discussed using multidisciplinary coupled-field, experimental and thermodynamic analysis methods.

2. Description and modeling of the system

2.1. System description

Fig. 1 shows the diagram of the proposed system, which consists of a methanol tank, a methanol pump, a solar PV hybrid heater, a solar PV-thermochemical hybrid reactor, a heat exchanger and a syngas storage tank. In the hybrid system, methanol is sequentially pumped from its storage tank into the heat exchanger and the heater; during this process, methanol is heated and/or vaporized by the dissipated heat from the PV modules and the recovered heat of the methanol and syngas mixture. Methanol vapor exiting the heater is transferred to the heat exchanger and then the reactor, where a part of the methanol is decomposed into syngas by dissipated heat from the PV modules. The methanol and syngas mixture is cooled in the heat exchanger and finally flows into the syngas storage tank, where the mixture is cooled to ambient temperature and methanol is condensed and recycled to the methanol tank. To facilitate the electricity generation efficiency evaluation, syngas from the tank is compressed and fed into the heat engine (i.e., gas and steam combined cycle, GSCC) for power generation.

2.2. Construction of the PV hybrid reactor

Fig. 2 displays a schematic diagram of the modular solar PV hybrid reactor, which consists of a point-focus Fresnel concentrator, an optical prism, a PV cell and a methanol decomposition reactor. The operation of the hybrid reactor comprises the following

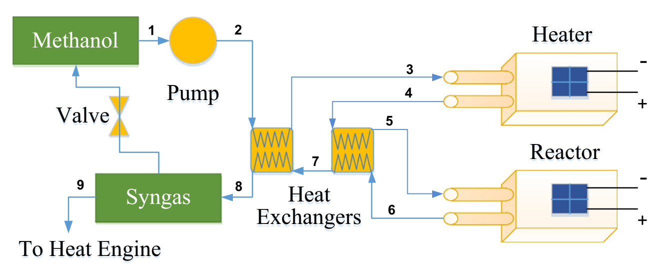

Fig. 1. Diagram of the hybrid system.

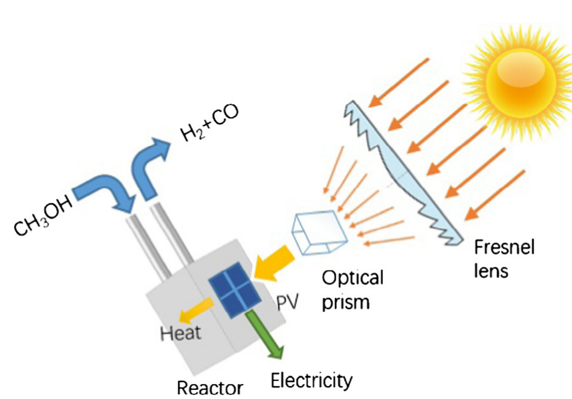

Fig. 2. Schematic diagram of the PV hybrid reactor: a point-focus Fresnel concentrator, an optical prism, a PV cell, and a methanol decomposition reactor.

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