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Investigation on the mid-temperature solar thermochemical power generation system with methanol decomposition☆

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HIGHLIGHTS

- A mid-temperature solar thermochemical power generation system is developed.
- The system off-design thermodynamic performances are numerically investigated.
- A small-scale pilot system is constructed and the power generation is achieved.
- The feasibility of solar thermochemical power technology is validated experimentally.

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ABSTRACT

A novel 1 MW_e mid-temperature solar thermochemical power generation system is proposed to improve solar conversion efficiency in this work. The system consists of a parabolic trough solar collector, solar receiver/reactor, syngas storage tank, internal combustion engine (ICE) and heat exchange devices. The fed methanol is evaporated and flows into the solar receiver/reactor for decomposition and to produce syngas (H_2 and CO), with the required reaction heat provided by the parabolic trough collector. Different from typical solar power technologies, in the proposed system, solar thermal energy is converted to syngas as chemical energy, which can be stored or utilized efficiently by an ICE for power generation. The thermodynamic performance evaluation results indicate that the annual energy efficiency and solar-to-electric efficiency reach to 33.78% and 18.29%, respectively. A small-scale pilot system with the capacity of 20 kW_e is constructed, and for the first time, an industrial-scale mid-temperature thermochemical power generation is realized, which experimentally validates the effectiveness of the novel solar power technology. The research findings provide an alternative means for improving solar conversion performances.

1. Introduction

Renewable energies, such as solar energy, biomass and wind, are considered as a promising approach to alleviating current energy and environmental concerns [1,2]. As a renewable source, solar energy can be concentrated and converted into thermal energy. Concentrated solar power (CSP) has been recognized as one of the most promising solutions for long-term green and renewable energy supplies. Various solar collection technologies continue to emerge, including line-focus technologies for the parabolic trough collector (PTC) and liner Fresnel, point-focus technologies for solar towers and solar dishes [3–7]. Solar irradiation is collected by a concentrator and then absorbed by a receiver, where irradiative heat is transferred into a heat transfer fluid (HTF), for example, molten salt and synthetic oil, as thermal energy, or utilized directly (as in direct steam generation technology) [8–10]. In a typical CSP system, solar irradiation is concentrated and used to produce high-temperature steam to drive a steam turbine for power generation.

The physical properties of the HTF and coating material of the solar receiver limit the collection temperature, particularly in parabolic trough solar power technology. Moreover, the intermittent nature leads to unfavorable thermodynamic performances and operation behaviors. Improvement in solar conversion efficiency is one of the major challenges in CSP technologies [11,12].

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Nomenclature

A	aperture area of solar collector
C	total surface concentration
DNI	direct nominal irradiation
E	activation energy
F	molar flow rate of the reactant
H	enthalpy
HHV	high heat value
k	rate constant
K	equilibrium constant
m	mass flow rate
p	partial pressure of component
P	electric power
Q	energy
r	conversion rate
R	universal gas constant
S	entropy
T	temperature

Greek

η	efficiency

subscript

ICE	internal combustion engine
sol-elec	solar-to-electric
sys	system

Different from technologies that use a thermal energy storage section with molten salts to improve solar conversion performance [13,14], the hybrid energy system that injects solar energy into mature-developed energy conversion processes provides a promising method. Numerous solar-based hybrid power systems have been developed in which the collected solar thermal energy can be integrated with coal, natural gas, and biomass, thereby achieving stable operation and improvement in solar conversion efficiency [15–20]. In addition, different trigeneration systems have been proposed, with biomass and solar energy for combined cooling, heating, and power (CCHP) production [21–23].

Moreover, solar thermochemistry forms part of a different hybrid routine, and includes solar driving H_2O/CO_2 splitting, gasification of carbonaceous materials, and natural gas reforming [24,25]. Solar thermal energy with an equivalent enthalpy change in endothermic reactions is converted into chemical energy of syngas. Therefore, the collected solar energy can be readily stored or efficiently utilized by an advanced power cycle (such as an ICE, gas turbine or combined cycle). Wang et al. [26] developed a local thermal non-equilibrium model to investigate heat and mass transfer performances of a porous media solar receiver in CH_4/H_2O reforming. Kruesi et al. [27] proposed a two-zone solar-driven gasifier concept, and experimentally evaluated the reaction characteristics of bagasse particles. Zeng et al. [28,29] conducted experimental research on solar-driven biomass pyrolysis using a solar concentrator with the maximum capacity of 1.5 kW and analyzed the characteristics and distributions of products. Guo et al. [30,31] and Bai et al. [32,33] investigated the thermodynamic performances of the solar gasification-based systems that produce Fischer-Tropsch liquid fuels, methanol and electricity. These solar thermochemical conversion processes offer various advantages in terms of increasing solar energy utilization performances and generating low carbon footprint gas fuel. However, the required solar collection temperature being excessively high ($> 800\,^\circ C$) leads to severe challenges in available collection efficiencies.

Furthermore, solar thermal energy can be used to drive mid-/low-temperature thermochemical reactions, such as methanol reforming and decomposition [34,35]. Hong and Jin [36,37] first proposed a mid-temperature solar thermochemistry concept to drive methanol reforming and produce syngas, whereby collected solar energy is converted into solar fuel and a PTC is integrated to provide the required solar thermal energy. The operation temperature of such a system is usually lower than 400 °C, which well matches the thermochemical reaction temperature. By means of the mid-temperature thermochemical process, solar thermal energy (250–350 °C) is converted into chemical fuel and the energy level is updated, which contributes to achieving higher solar conversion efficiency [38]. Liu et al. [39,40], Hong et al. [41] and Sui et al. [42] developed a 5–15 kW_{th} prototype solar receiver/reactor in which both the solar collection and thermochemical reaction are implemented simultaneously, and the experimental results validate the feasibility of solar-driven methanol steam reforming for hydrogen production. Moreover, Wang et al. [43] and Liu et al. [44] developed three-dimensional solar-methanol reforming/decomposition thermochemical models with porous catalyst bed, radiation/heat transfer/reaction characteristics were investigated and new solar collection configurations were proposed.

Mid-temperature solar thermochemistry technology with methanol reforming/decomposition provides a promising routine for improving solar conversion performances and can be employed by CSP generation systems. However, the above studies focused on the mechanisms of energy level upgrading and solar thermochemical reaction characteristics. In a solar power generation system, the solar-driven power cycle is significant in addition to the solar conversion sector, and it is affected by variations in solar irradiations and operation conditions. Therefore, it is important to analyze the long-term off-design operation characteristics of the system and conduct comprehensive comparisons with current typical CSP technologies. Furthermore, the technical feasibility of the solar thermochemical power generation, which is critical for future applications, should be validated experimentally.

Naturally, this work aims at developing a new CSP generation technology to improve solar conversion performances. The main contributions can be summarized as follows.

(1) With integration of the parabolic trough solar collection technology, a novel mid-temperature solar thermochemical power generation system is proposed in order to increase solar conversion efficiency. The collected solar energy is used to drive methanol decomposition in a solar receiver/reactor for producing syngas, rather than heating steam, which provides an alternative means of utilizing solar thermal energy efficiently. Furthermore, the temperature of the provided solar energy well matches with that of a thermochemical reaction, resulting in a lower exergy loss.

(2) The collected solar energy is converted into syngas chemical energy with the upgrade of the energy level. As a solar fuel, the produced syngas can be stored and utilized efficiently in an advanced power cycle. The off-design evaluation results demonstrate that the mid-temperature solar thermochemical power generation system achieves favorable thermodynamic performances and stable operation.

(3) A small-scale solar thermochemical power experimental system is developed, and continuous power generation with a full power load is achieved. It is the first time to realize the industrial-scale mid-temperature thermochemical power generation. More importantly, the technical feasibility of this novel solar power technology is validated experimentally.