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Research Paper

Performance investigation of a new distributed energy system integrated a solar thermochemical process with chemical recuperation

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HIGHLIGHTS

- A distributed energy system with solar thermochemical recuperation is proposed.
- The thermodynamic properties of the system are numerically investigated.
- The superiorities of the proposed system is demonstrated.

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ABSTRACT

A new distributed energy system that integrates a solar thermochemical process with chemical recuperation cycle is proposed. The methanol is converted into synthesis fuel through the endothermic decomposition reaction using the mid-and-low temperature solar energy in solar receivers/reactors, and the solar thermal energy is upgraded into the chemical energy of the synthesis fuel. The synthesis fuel releases its chemical energy in a micro gas turbine to drive a distributed energy system to output cooling, heating and power. A part of the flue heat from the synthesis fuel is stored and drives the methanol decomposition in a fixed bed reactor to replenish the synthesis fuel. Energy analysis and exergy analysis are implemented to evaluate the thermodynamics performances of the proposed system. Results indicate that the proposed system achieves a primary energy ratio of 75.42%, and the net efficiency of solar to electricity is 23.26% on the design condition. Due to the interaction of the thermochemical process and the energy storage, the power generation is insensitive to the variations of solar radiations, and has a good performance under varying user's load demands. The promising results can provide an efficient and stable utilization approach of the solar energy in distributed energy systems.

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1. Introduction

The efficient utilization of the solar energy contributes to saving the fossil energy and improving the environment condition [1]. Various solar power technologies, including photovoltaic (PV), concentrated solar power (CSP), solar thermochemical fuels, have been studied by many scientists [2–5]. Currently, the CSP employs the solar energy collected as an energy input to drive power cycles, such as the Rankle cycle and the Stirling cycle. The solar thermochemical process upgrades the solar heat to chemical energy of the fuel through endothermic reactions, and the solar energy can be stored and further used for the power generation as the form of the chemical energy.

Solar energy can drive various chemical reactions, such as water splitting, methane reforming, coal gasification, etc. [6–11]. Solar hydrogen from splitting water has inestimable value, which is limited by its high reaction temperature. Numerous researches have been carried out to achieve lower temperature of water splitting, and recent research progresses can be found in Ref. [12]. California Institute of Technology successfully conducted experiments through a two-step water-splitting thermochemical cycle using $CeO_2/CeO_{2-\delta}$ above 900 °C [13]. The catalytic reforming of methane is highly endothermic reaction favored by high temperatures. Both steam methane reforming (SMR) and dry methane reforming (DMR) driven by the concentrated solar thermal energy have been studied, some projects have been done to demonstrate this concept at a commercial scale [14]. CSIRO built a dual-coil, solar-tower reformer that can process 200 kW thermal natural gas at 850 °C. PNNL has developed a SMR prototype combined solar parabolic dish concentrators with micro- and meso-channel reactors, and

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Nomenclature

A	solar field area
E	exergy
F	mole flow rate
G	mass flow rate
H	enthalpy
Q	heat
T	temperature
X	conversion rate

Greek letters

η	efficiency

Subscript

0	ambient temperature
C	collected solar energy
ch	chemical energy
cov	conversion
h	heating
m	methanol
sol	solar energy
syn	synthesis gas
th	thermal energy

over 69% the solar-to-chemical conversion efficiency was achieved [15]. Other steam and dry gasification processes with the concentrated solar energy have been studied via numerical simulations and experiments. For example, Brandon established the reaction kinetics of solar gasification of biomass, analyzed the performances of pyrolysis and steam gasification of cellulose with the molten salts used as the catalyst and heat transfer media for solar gasification [16]. Ankan proposed a cleaner fossil power generation system integrated underground coal gasification with solar energy, shown a high net thermal efficiency of 32.9% [17].

So far, most of solar thermochemical reactions are carried out over 800 °C, that is the solar energy should be accomplished by high ratio solar concentrators, such as tower and dish concentrators. The thermochemical reaction of the methanol decomposition can utilize the low-to-medium temperature solar energy around 200–300 °C [18–21]. Compared with the high temperature solar thermochemical, the conversion from the mid-and-low temperature solar thermal energy to the chemical energy can achieve a higher upgrade. In addition, the traditional solar irradiation concentrators and receivers/reactors as usually more complicated than that of 200–300 °C solar thermochemical process. So the mid-and-low temperature solar thermochemical process with the methanol decomposition will be a promising approach to effectively utilize solar energy.

$$CH_3OH \rightarrow CO + 2H_2 \Delta H_{298K} = 90.1\ \text{kJ/mol} \quad (1)$$

Methanol can be cracked into H_2 and CO (synthesis gas) through the reaction driven by the mid-and-low temperature solar energy, and the solar energy can be stored as the chemical energy of the synthesis gas. Performance analysis and experimental demonstration have been implemented in our previous studies [22]. So, considering the characteristics of the mid-and-low temperature solar thermochemical process with the methanol decomposition, it has a great potential to be applied in a distributed energy system. Generally, the flue heat of the power cycles is used to output cooling through absorption chillers [23,24]. But, the flue gas temperature (280–550 °C) does not match well with the generator temperature (below 170 °C) of absorption chillers. In order to enhance the performances of the exhausted heat recovery, the chemical recuperation process is applied in the distributed energy system. Owing to the combined operation of the solar thermochemical and the chemical recuperation process, less scale solar field is required compared with traditional parabolic trough solar power plants. Due to the interaction of the thermochemical process and the chemical recuperation, the power generation is insensitive to the variations of solar radiations, and has a good performance under varying user's load demands.

Therefore, this study aims to propose a new distributed energy system to integrate the solar thermochemical and the chemical recuperation process with the methanol decomposition, and assess performances of the solar thermochemical and the chemical recuperation process. The main contributions are summarized as follows:

(1) A new distributed energy system integrating the solar thermochemical with the chemical recuperation process is proposed to effectively utilize the fossil fuel and the solar energy.
(2) In the proposed system, the solar energy and the flue heat are upgraded into the chemical energy via the thermochemical reaction of the methanol decomposition, and an effective integration utilization of the solar energy with the fossil fuel is achieved.
(3) The relationship between user's loads and the energy output of the proposed system is identified. The on-design and off-design thermodynamic performances and the characteristics of the system under varying solar radiations and user's loads are investigated.

The rest of this study is organized as follows. In Section 2, the novel system is proposed. In Section 3, numerical simulation models are presented. Thermodynamic performances are evaluated in Section 4. The main conclusions will be summarized in Section 5.

2. New system and performance analysis

The system process and key parameters are illustrated in this section, and operation strategies are shown. The solar thermochemical receivers/reactors are introduced to illustrate the operating characteristics, and several evaluation criteria are employed to evaluate the thermodynamic performances of the proposed system.

2.1. Descriptions of the new system

The solar energy can be efficiently utilized through the solar thermochemical reaction integrating the mid-and-low temperature solar energy with the methanol decomposition, and the solar energy can be stored as the chemical energy of the synthesis gas. The chemical recuperation process helps the exhausted heat recovery. Therefore, a novel distributed energy system integrating a solar thermochemical process with the chemical recuperation is proposed. This distributed energy system outputs cooling, heating,

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