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Solar-clean fuel distributed energy system with solar thermochemistry and chemical recuperation

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HIGHLIGHTS

- A new CCHP system with solar thermochemistry and chemical recuperation is proposed.
- Solar energy and exhaust heat are upgraded to high quality chemical energy of fuel.
- Favorable design and off-design thermodynamic performances are achieved.

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ABSTRACT

A new solar-hybrid fuel-fired distributed energy system incorporating thermochemical reaction driven by mid- and low-temperature solar heat and exhaust heat is proposed, for increased solar energy utilization and exhaust heat recovery efficiency. Solar energy is upgraded to syngas (H_2 and CO) chemical energy via the solar thermochemical process of the methanol decomposition reaction, and the syngas drives the internal combustion engine to output power. Some of the exhaust heat is stored and drives the methanol decomposition reaction to supplement the syngas via the chemical recuperation process, enhancing the exergy efficiency of the exhaust heat recovery. The overall energy efficiency and net efficiency of solar energy to electricity conversion are improved by integrating solar thermochemistry and chemical recuperation, and excellent off-design thermodynamic performance under varying user loads and solar irradiation levels is achieved. The overall energy efficiency, exergy efficiency, and net solar-energy-to-electricity efficiency reach 80.55%, 42.18% and 24.66%, respectively. These research findings indicate that the proposed system embodies an efficient and stable approach towards utilization of solar energy and clean fuel in distributed energy systems.

1. Introduction

With their high energy efficiency and low emission, distributed energy systems (DESs) are regarded as an energy-saving and environmentally friendly energy utilization approach [1]. Further, as a result of their local energy conversion and small-scale installation features, DESs and renewable energy utilization processes exhibit considerable compatibility [2,3].

Various types of renewable energy technology have been incorporated into DESs to reduce fossil energy consumption and promote development of renewable energy applications. In particular, biomass [4,5], wind energy and solar energy have been integrated with DESs [3,6,7], and many studies illustrating the associated system operation, thermodynamics and economy performance, operation strategies, etc., have been conducted. As a renewable energy, solar energy is widely regarded as a promising choice to replace fossil fuel and reduce the carbon emissions of energy conversion processes.

Solar-assisted DESs have lower fuel consumption and emissions than fossil-fuel-only energy systems, and lower costs than solar-only energy plants. A variety of ways are available to integrate solar energy technologies and DESs, and the energetic, economic, thermo-ecological cost [8] and environmental assessments are widely employed to evaluate the performances of solar-assisted DESs. Solar-powered combined cooling heating and power (CCHP) systems employing the Organic Rankine Cycle (ORC) have been proposed, in which the concentrated solar thermal energy first drives the ORC turbine to generate power and then the waste heat is then recycled to produce cooling and heat [9,10]. Wang et al. [11] have proposed a solar-driven CCHP system with an

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Nomenclature

CCHP	combined cooling, heating and power
DES	distributed energy system
ICE	internal combustion engine
ORC	organic Rankine cycle
A	solar collectors area
C	cooling
E	exergy
H	enthalpy
P	power
Q	energy
T	temperature
X	conversion rate
η	efficiency

Subscripts

a	ambient
che	chemical energy
cov	conversion
ele	electricity
ex	exergy
h	heat
s	sun
sol	solar energy
th	thermal energy

integrated Brayton cycle and transcritical CO_2 refrigeration cycle to produce power, cooling and heat. Solar thermal energy, which is concentrated by dish collectors, is used as the high-temperature heat source of the Brayton cycle, heating the supercritical CO_2 to drive the turbine for power generation. Further, Fani et al. [12] previously installed a solar-assisted CCHP system with solar thermal energy storage in an educational office building, and evaluated the energetic, economic and environmental performance of this proposed system. In addition, Li et al. [13] have analyzed multi-objective optimization of the thermal efficiency and thermo-economic performance of a 100 kW solar-dish regeneration Brayton system. In that system, fossil fuel is burned in the combustor and solar energy concentrated by a dish collector is transferred to the working fluid of the Brayton heat engine to reduce the fossil fuel combustion.

In the systems discussed in the literature, solar energy is mainly used as the high-temperature heat source of the power cycles (ORC, Brayton cycle, etc.) for power production, or to drive the refrigeration unit and heating system to output cooling and heat. However, the thermodynamics efficiency of solar-driven power cycles is limited by the Carnot efficiency, and remains at a low level for the low temperatures concentrated by solar thermal energy as the power cycles heat source. Further, raising the temperature of the concentrated solar heat increases the investment cost and complexity.

Given the shortages of the aforementioned solar-thermal CCHP systems, similar systems incorporating solar thermochemical processes have considerable potential to achieve enhanced thermodynamics and environmental performance. In a solar thermochemical process, solar energy is utilized to drive endothermic chemical reactions. Solar energy is upgraded to chemical energy of solar fuels through the solar thermodynamics process, which is stored with high stability and efficiency. Less exergy destruction occurs in the solar thermochemical process compared with the aforementioned solar-thermal conversion processes. Currently, solar thermochemical processes are widely employed in methane reforming [14], coal gasification, biomass gasification [15–17], etc. A 100 kWth solar-reactor pilot plant with a two-step water and CO_2 splitting cycle has been developed [18], along with a 200 kW solar-driven methane reformer [19], a 500 kW solar thermochemical reaction system of coal gasification [20], and a 150 kWth solar-driven carbonaceous materials gasification system [21]. These systems are operated with the solar thermochemical reaction temperature of more than 600 °C, being driven by solar tower or dish collectors. For DESs with solar thermochemistry, the solar energy is utilized efficiently in the form of solar fuel to drive the DESs to output power, cooling, and heat. Previously, Bianchini et al. [22,23] investigated a solar hybrid power system with solar thermochemistry of methane reforming, for which the fossil fuel saving rate was found to be approximately 20% compared with the a natural gas system without a solar thermochemical process. A hybrid solar-fossil-fuel plant incorporating the solar thermochemistry of methane reforming process has also been analyzed and optimized; the annual average thermal efficiency is reported to reach 47.59% [24]. In addition, the thermodynamics and environmental performance of a biogas-solar energy hybrid-driven CCHP system has been examined; this system is integrated with solar thermochemistry of biogas steam reforming, being driven by 750 °C solar thermal energy concentrated by parabolic dish collectors [25].

To date, the above-mentioned solar thermochemical processes are mainly driven by the high-temperature solar heat (above 600 °C), which is concentrated by high concentration ratio collectors. Sunlight is concentrated and absorbed as the thermal energy, and the heat loss and irreversible loss of the solar-to-heat conversion increases with increased solar thermochemical temperature. Increases in the solar thermochemistry temperature also generate a sharp increase in the system investment cost and complexity. Therefore, realization of a lower-temperature solar thermochemical process will be a promising approach to utilize the solar energy with high efficiency and low investment. The solar thermochemical reaction of methanol decomposition can be performed at approximately 200–300 °C as shown in Eq. (1). Thus, mid- and low-temperature solar thermal energy can be utilized through the thermochemical reaction of methanol decomposition, which can be accomplished by commercial parabolic trough collector (PTC). Compared with the high-temperature solar thermochemical process, a higher solar energy upgrade is achieved via the mid- and low-temperature solar thermochemistry process of methanol decomposition. In our previous research, many studies were performed [26–30], and thermodynamic performance of mid- and low-temperature solar thermochemistry have been numerical simulated and experimental validated [26,30,31]. Considering the technical advantages, the distributed energy system involving the mid- and low-temperature solar thermochemical process of methanol decomposition reaction is a promising approach to produce cooling, heat, and power.

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

In conventional CCHP systems, fuel is directly utilized by a gas turbine or internal combustion engine (ICE), and the exhaust heat is generally recycled to drive the absorption refrigerator to output cooling. However, the temperature of the exhaust heat (more than 400 °C) does not match the generation temperature (less than 150 °C) of the absorption refrigerator well [32]. Thus, the large temperature difference between the exhaust gas and generation process yields a low exergy efficiency in the exhaust heat recovery. For a DES incorporating mid- and low-temperature solar thermochemistry, the exergy efficiency of the exhaust heat recovery can be enhanced via a chemical recuperation process, with the exhaust heat being used to drive the thermochemical process of the methanol decomposition reaction. Thus, the exhaust heat is upgraded to syngas (H_2 and CO) chemical energy, which is then used efficiently. In this approach, the exhaust heat is first recycled via the chemical recuperation process and then used to drive the absorption refrigerator for cooling, thereby enhancing the exhaust