Postprint of a Combined Cooling, Heating and Power System Integrating Solar Thermochemistry and Chemical Heat Recuperation

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Abstract

A combined cooling, heating and power (CCHP) system integrating solar thermochemical and chemical recuperation processes is proposed. Solar energy is utilized to drive the methanol decomposition reaction; the produced syngas is combusted in an internal combustion engine to perform work, while the waste heat from the engine exhaust is exchanged with heat transfer oil to drive the methanol decomposition reaction for waste heat recovery. A thermodynamic performance analysis of the system is conducted, investigating the thermal performance and energy storage characteristics under typical days throughout the year. The research results indicate that under design conditions, the system' s primary energy utilization rate is 78.4%, and the solar net power generation efficiency is 21.1%. Within the direct irradiation intensity range of 300-1000 W/m^2, the system can achieve stable operation, with the solar net power generation efficiency stably varying within the range of 19.3%-21.5%.

Full Text

Preamble

Combined Cooling, Heating and Power System Integrating Solar Thermochemical and Chemical Recuperation Processes

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Abstract

This paper proposes a novel combined cooling, heating and power (CCHP) system that integrates solar thermochemical processes with chemical recuperation. Solar energy drives the methanol decomposition reaction, and the resulting syngas is combusted in an internal combustion engine to produce work. The engine' s exhaust waste heat is transferred to heat transfer oil, which then drives the methanol decomposition reaction to recover the residual heat. A thermodynamic performance analysis of the system is conducted to investigate the thermal performance and energy storage characteristics under typical daily conditions throughout the year. The results demonstrate that under design conditions, the system achieves a primary energy ratio of 78.4% and a net solar-to-electric efficiency of 21.1%. The system can operate stably within a direct solar irradiation range of 300-1000 W/m^2, maintaining a net solar-to-electric efficiency between 19.3% and 21.5%.

Keywords: solar thermochemical; energy storage; chemical recuperation; methanol decomposition

1. Introduction

Efficient utilization of solar energy is crucial for reducing fossil fuel consumption and greenhouse gas emissions. Current solar energy utilization primarily includes photovoltaic, solar thermal, and thermochemical approaches. Conventional solar thermal power generation typically involves heating a working fluid through a power cycle to produce electrical work [1-2]. Solar thermochemical power generation, however, employs concentrated solar thermal energy to drive endothermic chemical reactions, converting and storing solar heat in the chemical energy of fuel, thereby upgrading the energy grade of solar thermal energy and enabling efficient storage and utilization. Significant research progress has been achieved in utilizing high-temperature solar thermal energy above 700 °C to drive water and CO_2 splitting, coal gasification, and methane reforming [3-9]. However, numerous challenges remain in high-temperature solar thermochemical processes, including issues with solar absorber reactors, tracking systems, and catalysts that require urgent solutions. Mid- and low-temperature solar thermochemical technology, which employs solar thermal energy at 150–300 °C in combination with methanol thermochemistry, offers a new research direction for efficient solar energy utilization [10-12].

In distributed energy systems, power generation system exhaust waste heat is typically used directly to drive absorption chillers for cooling. However, the temperature of the exhaust heat does not always match well with the requirements of absorption refrigeration. To further enhance exhaust waste heat recovery and improve the operational stability of solar thermochemical power generation systems, this paper proposes a novel CCHP system based on methanol decomposition that combines solar thermochemical processes with chemical recuperation.

The thermodynamic performance of the system is analyzed under both design and off-design conditions.

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2. System Concept

Methanol, as a clean liquid fuel, can undergo decomposition reactions at 150–300 °C to produce hydrogen and carbon monoxide. The indirect combustion technology driven by solar-powered methanol decomposition [13] can increase the fuel heating value by approximately 20% while simultaneously reducing exergy losses during combustion and increasing the thermal exergy of the system. The relevant reaction equations are as follows:

Methanol decomposition reaction:
Syngas combustion reaction:

Currently, direct utilization of 400–500 °C gas engine exhaust to drive absorption chillers results in significant exergy losses due to large temperature differences during heat transfer. The proposed system utilizes the high-temperature section of engine exhaust to drive methanol decomposition, as illustrated in the process flow diagram [Figure 1: see original paper].

The system consists of five main components: (1) methanol feed preprocessing unit, (2) solar absorption/reaction unit, (3) chemical recuperation unit, (4) product separation and storage unit, and (5) power, cooling, and heating output unit. The working process is as follows: (1) Liquid methanol is converted to superheated steam after two-stage preheating; (2) Solar thermal energy concentrated by parabolic trough collectors drives the methanol decomposition reaction inside the absorber/reactor; (3) Engine exhaust heat is transferred to heat transfer oil, which then drives the methanol decomposition reaction in a fixed-bed reactor; (4) After cooling the high-temperature syngas and separating residual methanol, the syngas drives the internal combustion engine generator; excess syngas is stored in a syngas storage tank; (5) Engine exhaust waste heat is first stored as sensible heat of heat transfer oil through an oil-flue gas heat exchanger, then drives a double-effect lithium bromide absorption chiller for cooling production, and finally enters the methanol preheating unit; (6) Engine jacket water is used to heat domestic hot water. The solar thermochemical absorber/reactor is shown in [Figure 2: see original paper].

The system operates as follows: The solar absorption/reaction unit produces syngas to meet the engine’ s consumption demand. When production is insufficient, stored syngas is used preferentially, followed by operation of the chemical recuperation unit. Under sufficient solar irradiation, the solar absorption/reaction unit operates independently and stores excess syngas. Under insufficient solar irradiation, the chemical recuperation unit and solar absorption/reaction unit operate complementarily. When solar irradiation is zero, the chemical recuperation unit operates independently.

The main system features are: (1) Conversion of low-grade mid- and low-temperature solar thermal energy into high-grade chemical energy of syngas, enhancing the work capability of solar energy; (2) The chemical recuperation process strengthens exhaust waste heat recovery; (3) Coupled operation of solar thermochemical and chemical recuperation processes improves system operational stability and extends operating duration.

2.1 Simulation Conditions

The proposed system is designed based on structural parameters from the solar thermochemical power generation experimental base of the Institute of Engineering Thermophysics, Chinese Academy of Sciences, located in Langfang, Hebei Province, as listed in . The parabolic trough solar collector field is arranged in a north-south orientation, and meteorological data are obtained from local measurements by a BSRN3000 weather station. The real-time variation curves of solar direct normal irradiance (DNI) on typical days throughout the year are shown in [Figure 3: see original paper].

The collector efficiency calculation model [15] is:

where _{opt} is the optical efficiency of the solar concentrator field; K_ is the cosine correction coefficient of the parabolic solar collector; is the emissivity of the absorber/reactor; a, b, and c are coefficients determined by the collector tube dimensions; I is the solar direct irradiance (W/m^2); v_w is the wind speed (m/s); T_c, T_a, and T_{sky} are the collector temperature, ambient temperature, and sky temperature, respectively.

2.2 System Performance Evaluation Criteria

The system performance is evaluated using several metrics: system thermal efficiency, system exergy efficiency, system power generation efficiency, net solar-to-electric efficiency, and solar share.

The solar energy input Q_{solar} is calculated as:

where A is the aperture area of the collector field (m^2).

System thermal efficiency (_{th}) is defined as the ratio of total system output to total energy input, measuring the system’ s energy utilization:

where P is the system power output, Q_h is the heating load, C is the cooling load, Q_{solar} is the solar energy input, m_{methanol} is the methanol consumption rate, and h_{methanol} is the enthalpy of methanol.

System exergy efficiency (_{ex}) is the ratio of output exergy to total input exergy, reflecting energy quality utilization and optimization potential of system components:

where T__0, T__h, T__c, and T__s are the ambient temperature, heating temperature, chilled water outlet temperature, and solar collector temperature, respectively.

System power generation efficiency (__e) is the ratio of total electrical work output to total energy input, directly reflecting power generation performance.

The system' s energy input includes both solar energy and methanol chemical energy. Net solar-to-electric efficiency (__{solar}) is introduced to evaluate solar energy utilization efficiency:

where h__{methanol} is the enthalpy per mole of methanol fuel, and h__{syngas} is the enthalpy of syngas after complete methanol decomposition.

Solar share (S__{solar}) is introduced to reflect the proportion of solar energy in the total energy input, indicating the degree of solar energy utilization:

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3. Results and Discussion

Thermodynamic performance analysis is conducted for the system under both design and off-design conditions to investigate the thermal performance and energy storage characteristics on typical days throughout the year.

3.1 Design Condition System Performance

Energy balance analysis for the design condition yields the results shown in . Under a rated power output of 100 kW, the total energy input is 309.58 kW, with solar energy input accounting for 58.80 kW (18.99% of total input), demonstrating fossil fuel savings. At the design irradiance of 700 W/m^2, the solar integrated absorber/reactor produces syngas that meets the engine' s full-load operation demand, with 15.39 kW of excess syngas stored in the syngas tank. Following the principle of energy cascade utilization, engine exhaust first stores 17.64 kW of high-temperature waste heat as sensible heat of heat transfer oil, then drives a double-effect lithium bromide absorption chiller to produce 23.86 kW of cooling, and finally enters the methanol preheating unit. Under design conditions, the system achieves a primary energy ratio of 78.4%, power generation efficiency of 34.0%, and net solar-to-electric efficiency of 21.1%.

TABLE:2 Energy balance analysis under design condition

Parameter	Value (kW)
Total energy input	309.58
Methanol chemical energy	250.78
Total energy output	242.50
Stored syngas	15.39
Energy utilization ratio	78.4%

Parameter	Value (kW)
System power generation efficiency	34.0%
Net solar-to-electric efficiency	21.1%

To deepen the performance analysis and identify improvement potential, exergy analysis is conducted from an energy quality perspective, with results shown in . The system exergy efficiency under design conditions is 45.6%. The largest exergy loss occurs in the internal combustion engine, accounting for 42.2% of total input exergy, due to significant irreversible losses during the conversion of fuel chemical energy to physical energy during syngas combustion. The solar collector efficiency is 0.65 under design conditions, resulting in substantial exergy losses in the solar absorber/reactor (4.1% of total input exergy). Additionally, significant exergy losses also occur in engine jacket water heating and the absorption chiller.

Components with large exergy losses represent potential areas for system improvement. Further optimization of the internal combustion engine, solar absorber/reactor, jacket water heating, and double-effect absorption chiller can enhance system thermodynamic performance.

TABLE:3 Exergy balance under design condition

Component	Exergy loss (kW)	Percentage (%)
Solar absorber/reactor	15.2	4.1
Heat transfer oil storage	8.5	2.3
Jacket water heating	12.8	3.5
Absorption chiller	18.6	5.0

3.2 Off-design System Performance

Under variable irradiation conditions, the performance of the solar thermochemical reaction unit changes with solar flux. By regulating the chemical recuperation unit and syngas storage unit, stable operation of the power equipment can be achieved, enhancing system operational stability. The relationship between net solar-to-electric efficiency and solar share with irradiation is shown in [Figure 4: see original paper].

As solar direct irradiance increases from 300 to 700 W/m^2, the methanol chemical energy input remains essentially stable while solar energy input gradually increases, causing the solar share to rise from 9.6% to 19.0%. As irradiance increases from 700 to 1000 W/m^2, excess syngas is actively stored and the methanol fuel chemical energy input also increases, resulting in a slow change in solar share. The figure demonstrates that the system maintains high solar utilization efficiency and good operational stability under variable irradiation, with net solar-to-electric efficiency remaining within the range of 19.3%-21.5% across the 300-1000 W/m^2 irradiance range, indicating efficient utilization even at low irradiance levels.

3.3 Annual Typical Day System Performance Analysis

Solar irradiation varies significantly with seasons, and solar azimuth angle and ambient temperature also affect collector performance. Therefore, typical days throughout the year are selected to analyze the system' s variable irradiation performance and characterize the relationship between energy input and storage, elucidating the coupling dynamics among the solar absorber/reactor, fixed-bed reactor, and storage units.

[Figure 5: see original paper] illustrates the real-time variation relationships among solar energy input, chemical energy input, syngas storage, and heat storage on typical days, demonstrating system operational characteristics and storage variation patterns under different irradiation conditions. Taking the summer typical day as an example: during 7:00–16:00, sufficient solar irradiation enables the solar thermochemical reaction unit to produce syngas that meets engine demand, with excess syngas stored; during 16:00–18:00, insufficient solar irradiation requires releasing stored syngas to supplement production and maintain full-load engine operation; during 7:00–18:00, portion of flue gas waste heat is recovered as sensible heat of heat transfer oil, gradually increasing stored heat; during 18:00–7:00, minimal or zero solar irradiation necessitates releasing stored oil sensible heat to drive methanol decomposition in the fixed-bed reactor to meet power unit demand, causing stored heat to decrease.

The north-south collector arrangement results in larger cosine losses in winter, leading to relatively low collector efficiency. Additionally, shorter daylight hours and lower ambient temperatures in winter reduce solar energy input, preventing the solar thermochemical reaction unit from independently meeting engine demand (syngas storage remains zero). Complementary operation of the fixed-bed reactor and solar thermochemical unit satisfies the syngas demand, enabling 9.0 hours of continuous full-load operation on the winter solstice.

[Figure 6: see original paper] compares the total cooling, heating, and power (C, Q, W) outputs and daily average performance metrics (system power generation efficiency _e, net solar-to-electric efficiency _{solar}, solar share S_{solar}, and operating duration) across four typical seasonal days. The summer solstice achieves 24.0 hours of continuous operation with total power generation of 8.64 GJ, system power generation efficiency of 36.7%, and net solar-to-electric efficiency of 20.6%. Even under low irradiance, low temperature, and large cosine loss conditions on the winter solstice, the system operates continuously for 9.0 hours with daily power generation of 3.25 GJ, system efficiency of 33.4%, net solar-to-electric efficiency of 12.8%, and solar share of 15.9%.

3.4 Annual Performance Characteristics

Annual performance analysis reveals that due to abundant solar irradiation and smaller incidence angles in summer and autumn, more solar energy is input to the system compared with spring and winter, resulting in significantly higher net power generation and system efficiency during summer and autumn months.

Monthly net solar-to-electric efficiency and solar share are shown in [Figure 8: see original paper]. Abundant solar input and small cosine losses in summer and autumn yield higher net solar-to-electric efficiency than in spring and winter. However, longer operating durations and higher methanol fuel chemical energy input during summer and autumn result in slightly lower solar shares compared with winter months. The monthly thermodynamic analysis yields annual average power generation efficiency of 35.7% and annual average net solar-to-electric efficiency of 18.5%.

4. Conclusions

To improve operational stability of solar thermochemical hybrid power systems and enhance waste heat recovery from power generation systems, a novel CCHP system integrating solar thermochemical processes with chemical recuperation based on methanol decomposition is proposed. Thermodynamic performance analysis under design and off-design conditions yields the following main conclusions:

1. Utilizing mid- and low-temperature solar thermal energy (200–300 °C) and stored internal combustion engine flue gas waste heat to drive methanol decomposition produces syngas. This approach reduces exergy losses during combustion by decreasing fuel grade in the decomposition process while simultaneously enhancing the work capability of mid- and low-temperature solar thermal energy and flue gas waste heat through conversion to high-grade fuel chemical energy.
2. Under design conditions, the system achieves a primary energy ratio of 78.4%, net solar-to-electric efficiency of 21.1%, and exergy efficiency of 45.6%. Within the direct irradiance range of 300–1000 W/m^2, net solar-to-electric efficiency remains stable at 19.3%–21.5%. Integration of chemical recuperation with solar thermochemical processes improves net solar-to-electric efficiency and operational stability under variable irradiation, particularly enhancing utilization efficiency at low irradiance levels.
3. On typical days, the system power equipment operates at full load, stably outputting electricity, heat, and cooling. The system operates continuously for 24.0 hours on the summer solstice with daily net solar-to-electric efficiency of 20.6%, and for 9.0 hours on the winter solstice with daily

net solar-to-electric efficiency of 12.8% and solar share of 15.9%. The annual average power generation efficiency is 35.7% with annual average net solar-to-electric efficiency of 18.5%. The system demonstrates advantages of long continuous operation duration, high net solar-to-electric efficiency, and outstanding energy-saving performance.

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