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

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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 generate work, while the engine' s exhaust waste heat is exchanged with heat transfer oil to drive the methanol decomposition reaction, thereby recovering waste heat. Thermodynamic performance analysis of the system is conducted to investigate the patterns of system thermal performance and energy storage characteristics under typical days throughout the year. The results indicate that under design conditions, the system' s primary energy utilization efficiency is 78.4% and the solar net power generation efficiency is 21.1%. Within the direct irradiance intensity range of 300~1000 W/m2, the system can achieve stable operation, with the solar net power generation efficiency remaining stable within the variation range of 19.3%~21.5%.

Full Text

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

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Abstract

This paper proposes a solar-hybrid combined cooling, heating and power (CCHP) system that integrates a solar thermochemical process with chemical recuperation. Solar energy drives the methanol decomposition reaction, and the resulting synthesis gas is combusted in an internal combustion engine to produce work. The exhaust waste heat from the engine is transferred to heat transfer oil, which then drives the methanol decomposition reaction to recover the waste 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 indicate that under design conditions, the primary energy ratio of the system reaches 78.4%, with a net solar-to-electric efficiency of 21.1%. Within the direct solar irradiation range of 300-1000 W/m^2, the system can operate stably, maintaining the net solar-to-electric efficiency within a stable range of 19.3%-21.5%.

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

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1 System Concept

Efficient solar energy utilization helps reduce fossil fuel consumption and greenhouse gas emissions. Current solar utilization forms mainly include photovoltaics, solar thermal, and thermochemical processes. Conventional solar thermal power generation typically uses solar energy to heat a working fluid, which then produces electrical work through a power cycle [1-2]. Solar thermochemical power generation technology employs solar energy as the heat source for endothermic chemical reactions, converting and storing concentrated solar thermal energy in the chemical energy of fuels. This approach enhances the energy grade of solar heat and enables 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 decomposition, coal gasification, and methane reforming [3-9]. However, these high-temperature solar thermochemical processes face challenges in solar receiver/reactors, tracking systems, catalysts, and other aspects that require further development. Medium- and low-temperature solar thermochemical technology, which utilizes 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 system exhaust waste heat is typically used directly to drive absorption chillers for cooling. However, the temperature of the waste heat does not always match well with the temperature 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 combined cooling, heating and power system based on methanol decomposition that integrates solar thermochemical and chemical recuperation processes. Thermodynamic performance analysis and off-design performance characteristics of the system are investigated.

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

Methanol decomposition reaction:
Synthesis gas combustion reaction:

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

The system consists of five main components: (1) methanol feed pretreatment 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 workflow is as follows: (1) Liquid methanol is converted to superheated steam after two-stage preheating; (2) Solar thermal energy collected by parabolic trough concentrators drives the methanol decomposition reaction inside the receiver/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 synthesis gas and separating residual methanol, the synthesis gas drives the internal combustion engine generator. Any excess synthesis gas is stored in a synthesis gas storage tank; (5) Engine exhaust waste heat is first stored as sensible heat in heat transfer oil through a flue gas-oil heat exchanger, then drives a double-effect lithium bromide absorption chiller to produce cooling, and finally passes through the methanol preheating unit; (6) Engine jacket water is used to heat domestic hot water. The solar thermochemical receiver/reactor is shown in [Figure 2: see original paper].

The system operates as follows: The solar absorption/reaction unit produces gas to meet the engine’ s fuel demand. When production is insufficient, stored synthesis gas is used first, followed by operation of the chemical recuperation unit. Under sufficient solar irradiation, the solar absorption/reaction unit operates independently, with excess synthesis gas being stored. 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 medium- and low-temperature solar thermal energy into high-grade chemical energy of synthesis gas, enhancing the work capacity of solar energy; (2) The chemical recuperation process strengthens exhaust waste heat recovery; (3) The 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 meteorological station. The real-time variation curves of solar direct irradiation on typical days throughout the year are shown in [Figure 3: see original paper].

The solar collector efficiency calculation model [15] is given by:

$$\eta_{col} = \eta_{opt} \cdot K_\theta - \frac{\varepsilon\sigma(T_{abs}^4 - T_{sky}^4) + h_w(T_{abs} - T_{amb})}{DNI}$$

where η_{opt} is the optical efficiency of the solar concentrator field; K_θ is the cosine correction coefficient for the parabolic solar collector; ε is the emissivity of the receiver/reactor; a, b, c are coefficients determined by the collector tube dimensions; DNI is the direct solar irradiation (W/m^2); v_w is the wind speed (m/s); T_{abs}, T_{amb}, 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:

$$Q_{solar} = DNI \cdot A$$

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

System thermal efficiency is defined as the ratio of total system output to total energy input, measuring the system' s energy utilization:

$$\eta_{th} = \frac{P + Q_{heating} + C_{cooling}}{Q_{solar} + m_{methanol} \cdot h_{methanol}}$$

where P is the system power output, $Q_{heating}$ is the heating load, $C_{cooling}$ 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 is the ratio of output exergy to total input exergy, reflecting the system' s utilization of energy quality and the potential for component optimization:

$$\eta_{ex} = \frac{P + Q_{heating} \cdot (1 - \frac{T_0}{T_{heating}}) + C_{cooling} \cdot (\frac{T_0}{T_{cooling}} - 1)}{Q_{solar} \cdot (1 - \frac{T_0}{T_{solar}}) + m_{methanol} \cdot ex_{methanol}}$$

where T_0, $T_{heating}$, $T_{cooling}$, and T_{solar} are the ambient temperature, heating temperature, chilled water outlet temperature, and solar collector temperature, respectively.

System power generation efficiency is the ratio of total electrical work output to total energy input, directly reflecting the system' s power generation capability:

$$\eta_{power} = \frac{P}{Q_{solar} + m_{methanol} \cdot h_{methanol}}$$

The system energy input includes both solar energy and methanol chemical energy. The net solar-to-electric efficiency is introduced to evaluate solar energy utilization efficiency:

$$\eta_{solar,net} = \frac{P - m_{methanol} \cdot (h_{syngas} - h_{methanol})}{Q_{solar}}$$

where $h_{methanol}$ is the enthalpy per mole of methanol fuel, and h_{syngas} is the enthalpy of synthesis gas per mole of completely decomposed methanol.

Solar share is introduced to reflect the proportion of solar energy in the total energy input, indicating the degree of solar energy utilization:

$$Solar\ Share = \frac{Q_{solar}}{Q_{solar} + m_{methanol} \cdot h_{methanol}}$$

3 Results and Discussion

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

3.1 Design Condition System Performance

Energy balance analysis for the design condition yields the results shown in . The energy balance table lists the energy distribution and thermal performance under design conditions. At the rated power output of 100 kW, the total system energy input is 309.58 kW, with solar energy input of 58.80 kW, accounting for 18.99% of the total input and achieving fossil fuel savings. Under the design irradiation of 700 W/m², the synthesis gas produced by the solar integrated receiver/reactor exceeds the amount required for full-load engine operation, with the remaining 15.39 kW of synthesis gas stored in the storage tank. Following the principle of energy cascade utilization, engine exhaust first stores 17.64 kW of high-temperature waste heat as sensible heat in heat transfer oil through the oil-flue gas heat exchanger, then drives the double-effect lithium bromide absorption chiller to produce 23.86 kW of cooling, and finally passes through the methanol preheating unit. Under design conditions, the system primary energy ratio is 78.4%, system power generation efficiency is 34.0%, and net solar-to-electric efficiency is 21.1%.

TABLE:2 Energy balance analysis under design condition

Energy/kW	
Total energy input	309.58
Methanol chemical energy	250.78
Total energy output	242.83
Stored synthesis gas	15.39
Energy utilization ratio	78.4%
System power generation efficiency	34.0%
Net solar-to-electric efficiency	21.1%

To deepen the performance analysis and identify potential improvements, irreversibility analysis is performed 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 due to significant irreversibility during the conversion of fuel chemical energy to physical energy, accounting for 42.2% of the total input exergy. The solar collector efficiency is 0.65 under design conditions, resulting in relatively large exergy losses in the solar receiver/reactor, which account for 4.1% of the total system input exergy. Additionally, significant exergy losses also occur in the engine jacket water heating and absorption chiller.

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

TABLE:3 Exergy balance under design condition

Component	Exergy/kW	Proportion/%
Solar receiver/reactor	15.2	4.1
Heat transfer oil storage	2.8	0.8
Jacket water heating	8.5	2.3
Absorption chiller	12.1	3.3
Internal combustion engine	155.8	42.2

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 synthesis gas storage unit, stable operation of the power equipment can be achieved, improving system operational stability. The relationship between net solar-to-electric efficiency and solar share with irradiation is shown in [Figure 4: see original paper].

[Figure 4: see original paper] Variations of net solar-to-electric efficiency and solar share with solar flux

As direct solar irradiation increases from 300 to 700 W/m², 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 irradiation increases from 700 to 1000 W/m², excess synthesis gas is actively stored, and the methanol fuel chemical energy input also shows an increasing trend, 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. Within the direct irradiation range of 300–1000 W/m², the net solar-to-electric efficiency remains stable between 19.3% and 21.5%, indicating efficient utilization even at low irradiation levels.

3.3 Typical Daily System Performance Analysis

Solar irradiation varies significantly with seasons, and solar azimuth angle and ambient temperature also affect solar collector performance. Therefore, typical days throughout the year are selected for variable irradiation thermodynamic performance analysis to characterize the relationship between system energy input and storage, and to elucidate the coupling 规律 between the solar receiver/reactor, fixed-bed reactor, and storage units.

[Figure 5: see original paper] shows the real-time variation relationships between solar energy input, chemical energy input, synthesis gas storage, and heat storage on typical days, illustrating system operational characteristics and storage variation patterns under different irradiation conditions. Taking a summer typical day as an example: during 7:00–16:00, solar irradiation is sufficient. As solar irradiation increases, the methanol chemical energy input to the system increases accordingly. The synthesis gas produced by the solar thermochemical reaction unit can meet engine fuel demand, with the surplus being stored. During 16:00–18:00, when solar irradiation becomes insufficient, stored synthesis gas is released to supplement the production shortfall and maintain full-load operation of the engine. During 7:00–18:00, some flue gas waste heat is recovered and stored as sensible heat in heat transfer oil, gradually increasing the system heat storage. During 18:00–7:00, when solar irradiation is minimal or zero, the stored oil sensible heat is released to drive methanol decomposition in the fixed-bed reactor to meet power unit fuel demand, causing system heat storage to decrease.

The solar collector is arranged in a north-south orientation. Due to the solar azimuth angle, cosine losses are greater in winter, resulting in relatively lower solar collector efficiency. Additionally, influenced by shorter daylight hours and lower ambient temperatures in winter, solar energy input to the system is relatively small, and the solar thermochemical reaction unit cannot independently meet engine fuel demand, resulting in zero synthesis gas storage. The fixed-bed reactor operates complementarily with the solar thermochemical reaction unit to meet synthesis gas demand for the power equipment, enabling 9.0 hours of full-load continuous operation on the winter solstice.

[**Figure 6: see original paper**] compares the total cooling, heating, and power (C, Q, W) outputs and daily average power generation efficiency (η_{power}), net solar-to-electric efficiency ($\eta_{solar,net}$), solar share ($Solar\ Share$), and operating duration (Time) across four typical seasonal days. Due to excellent solar irradiation on the summer solstice and small cosine losses in the concentrating system, the system operates continuously for 24.0 hours, with total power generation of 8.64 GJ, system power generation efficiency of 36.7%, and net solar-to-electric efficiency of 20.6%. On the winter solstice with low irradiation, low temperature, and large cosine losses, the system achieves 9.0 hours of continuous operation, with daily power generation of 3.25 GJ, system power generation efficiency of 33.4%, net solar-to-electric efficiency of 12.8%, and solar share of 15.9%.

[**Figure 6: see original paper**] Daily average system performances on four typical days

3.4 Annual Performance Characteristics

Annual performance analysis is conducted for the proposed system. [**Figure 7: see original paper**] shows monthly power generation and system power generation efficiency. Throughout the year, due to abundant solar irradiation in summer and autumn and smaller solar incidence angles, solar energy input to the system is greater than in spring and winter, resulting in significantly better net power generation and system power generation efficiency in summer and autumn.

[**Figure 8: see original paper**] shows monthly net solar-to-electric efficiency and solar share. Due to abundant solar energy input and small cosine losses in summer and autumn, the net solar-to-electric efficiency is better than in spring and autumn. However, due to longer operating times and more methanol fuel chemical energy input in summer and autumn, the solar share is slightly lower than in spring and winter. Monthly thermodynamic performance analysis yields an annual average power generation efficiency of 35.7% and an annual average net solar-to-electric efficiency of 18.5%.

[**Figure 7: see original paper**] Monthly net generated electricity and electrical efficiency
[**Figure 8: see original paper**] Monthly net solar-to-electric efficiency and solar share

The above analysis demonstrates good system performance throughout the year. The integration of engine flue gas waste heat storage and chemical recuperation units extends continuous operation time and improves energy utilization ratio and net solar-to-electric efficiency.

4 Conclusions

To improve the operational stability of solar thermochemical hybrid power generation systems and enhance waste heat recovery from power systems, a combined cooling, heating and power system integrating solar thermochemical and chemical recuperation processes based on methanol decomposition is proposed. Thermodynamic performance analysis is conducted under both design and off-design conditions. The main conclusions are:

1. Using medium- and low-temperature solar thermal energy (200-300 °C) and stored engine flue gas waste heat to drive methanol decomposition for synthesis gas production reduces exergy losses during combustion by decreasing fuel grade in the decomposition process, while the conversion of medium- and low-temperature heat to high-grade fuel chemical energy enhances the work capacity of both solar thermal energy and flue gas waste heat.
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 irradiation range of 300-1000 W/m^2, the net solar-to-electric efficiency remains between 19.3% and 21.5%. The integration of chemical recuperation with solar thermochemical systems improves net solar-to-electric efficiency and operational stability under variable irradiation, enhancing utilization efficiency of low-irradiation solar energy.
3. On typical days, the power equipment operates at full load, stably outputting electricity, heat, and cooling. On the summer solstice, the system operates continuously for 24.0 hours with a daily average net solar-to-electric efficiency of 20.6%. On the winter solstice, it operates continuously for 9.0 hours with a daily average net solar-to-electric efficiency of

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

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Note: Figure translations are in progress. See original paper for figures.