Research on Solar-Driven Biomass Gasification Power Generation Systems: Postprint

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Abstract

This paper proposes a novel power generation system based on solar-driven biomass gasification, utilizing a tower heliostat field to concentrate solar energy and generate high-temperature solar thermal energy at 1000-1500K to drive biomass gasification reactions, and integrating an advanced gas-steam combined cycle power generation system for efficient utilization of the gasified syngas. Thermodynamic performance analysis of this system was conducted. The results show that, compared with conventional biomass gasification methods, driving biomass gasification reactions not only converts intermittent solar energy into stable chemical energy of syngas, but also increases the chemical energy of the gasified syngas. Additionally, the molar ratio of H_2 to CO in the syngas reaches 1.65-2.44 at gasification temperatures of 1000-1500K, which is favorable for direct synthesis of clean liquid fuels such as methanol. Under design conditions, the solar-to-power conversion efficiency of the system will reach 23.68%. As the gasification reaction temperature increases, the solar share of the system and the output electric power increase, while both the total thermal efficiency and total exergy efficiency of the system decrease. The research findings will provide an effective approach for the efficient utilization of abundant solar energy and comprehensive biomass energy utilization in western China.

Full Text

Investigation of a Solar-Driven Biomass Gasification Power Generation System

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Abstract

This paper proposes a novel power generation system based on solar-driven biomass gasification. The system utilizes a solar tower heliostat field to concentrate solar energy and generate high-temperature thermal energy at 1000-1500 K to drive biomass gasification reactions, which is then integrated with an advanced gas-steam combined cycle for efficient utilization of the produced syngas. Thermodynamic performance analysis of the system reveals that, compared with conventional biomass gasification methods, driving the gasification reaction with solar energy not only converts intermittent solar energy into stable chemical energy of syngas but also increases the chemical energy content of the product gas. The molar ratio of H_2 to CO in the syngas reaches 1.65-2.44 at gasification temperatures of 1000-1500 K, which is favorable for direct synthesis of clean liquid fuels such as methanol. Under design conditions, the solar-to-electricity conversion efficiency of the system reaches 23.68%. As the gasification temperature increases, both the solar share and electrical power output increase, while the overall thermal and exergy efficiencies decrease. These research results provide an effective pathway for the efficient integrated utilization of abundant solar and biomass resources in western China.

Keywords: solar energy; biomass gasification; power generation; performance analysis

Introduction

To address increasingly severe energy shortages and environmental pollution, countries worldwide are vigorously developing renewable energy sources such as solar and biomass. Compared with direct combustion, biomass can be converted into high-quality gaseous fuel rich in CO and H_2 through gasification. This syngas can be efficiently utilized in gas-steam combined cycle units and also serve as feedstock for producing various chemical products such as methanol and dimethyl ether [1, 2]. Conventional biomass gasification technology employs autothermal operation to provide reaction heat, which simplifies the gasification process and reduces technical requirements for the reactor but suffers from several drawbacks: (1) approximately 20%-40% of the biomass must be consumed to provide gasification heat, reducing the effective utilization rate of biomass [3]; and (2) the relatively high CO_2 and N_2 content in the syngas results in low heating value and limits its application scope [4, 5].

In regions rich in both solar and biomass resources, high-temperature concentrated solar energy can serve as a driving heat source for biomass gasification. This approach not only converts intermittent and unstable solar energy into high-quality chemical energy of syngas, achieving stable solar energy storage, but also avoids many shortcomings of conventional gasification technology [5-7]. Based on this concept, Kalinci et al. [8] constructed a biomass gasification-based hydrogen production system driven by high-temperature solar energy and conducted thermodynamic performance analysis, obtaining syngas with H_2 content of 48%-57.6%, which is superior to conventional fossil fuel gasification systems. Piatkowski et al. [9] designed packed-bed solar gasification reactors and conducted experimental studies on gasification characteristics of different hydrocarbons. Ng et al. [10] and Kaniyal et al. [11] subsequently proposed polygeneration systems utilizing solar-driven gasification of biomass or fossil fuels, integrating combined cycle power generation and Fischer-Tropsch synthesis systems for producing electricity and liquid fuels. This paper combines the regional resource status of renewable energy and proposes a multi-energy complementary utilization method that directly integrates solar-biomass gasification with syngas combustion power generation.

Using cotton stalks from Xinjiang region as feedstock and high-temperature concentrated solar energy as the gasification heat source, this study investigates the characteristics of biomass steam gasification, analyzing the influence of different gasification temperatures and other factors on gasification behavior and syngas composition. A solar-driven biomass gasification power generation system is proposed, and its thermodynamic performance is evaluated based on both the first and second laws of thermodynamics.

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1. Biomass Gasification and Sample Basic Properties

Biomass gasification is a complex thermochemical reaction system that undergoes four stages—drying, pyrolysis, oxidation, and reduction—to complete the transformation into gaseous fuel. The solar-biomass gasification method using steam as the gasifying agent employs external heat provided by high-temperature solar concentrators to replace the oxidation reaction process in conventional biomass gasification, reducing biomass consumption for combustion while avoiding dilution of syngas by large amounts of CO_2 from oxidation reactions and N_2 from air.

The gasification process includes heterogeneous gas-solid reactions between gasifying agents or gaseous products and solid fuel, as well as homogeneous reactions between gaseous products or gasifying agents. The main gasification reactions are as follows:

$C + H_2O \rightarrow CO + H_2 \qquad \Delta\ H_{298}K = 131.29$ kJ/mol
$C + CO_2 \rightarrow 2CO \qquad \Delta\ H_{298}K = 172.46$ kJ/mol
$C + 2H_2 \rightarrow CH_4 \qquad \Delta\ H_{298}K = -74.81$ kJ/mol
$CH_4 + H_2O \rightarrow CO + 3H_2 \qquad \Delta\ H_{298}K = 206.10$ kJ/mol
$CO + H_2O \rightarrow CO_2 + H_2 \qquad \Delta\ H_{298}K = -41.17$ kJ/mol

Xinjiang region in China is exceptionally rich in solar resources, with annual sunshine hours of 2500-3550 h and total annual horizontal surface solar irradiation of 5000-6400 MJ/m^2. Xinjiang is also China’ s major cotton-producing region, with cotton output reaching 4.35×10^6 t in 2012, accounting for 57%

of national production. The abundance of both solar and biomass resources provides a solid foundation for achieving efficient integrated utilization of these two renewable energy sources.

The biomass sample selected for this study is cotton stalk obtained from the Korla region of Xinjiang. The basic physicochemical properties of the sample were experimentally determined and are presented in Tables 1-3.

Proximate analysis of sample
Ultimate analysis and heat value of sample
Melting properties of the biomass ash

Based on meteorological parameters from Korla, Xinjiang, September 22 was selected as the design condition point, with direct normal irradiance (DNI) and incident angle chosen as 744 W/m^2 and 33.32°, respectively. The thermal efficiency _{col} of the tower-type high-temperature solar gasification absorber/reactor at the design point is 48.38%.

2.1 System Flow

Utilizing concentrated solar energy to provide sufficient external heat for biomass gasification not only improves gasification characteristics but also achieves conversion of solar energy into syngas chemical energy. Based on this principle, an advanced gas-steam combined cycle power generation system is integrated to construct the solar-driven biomass gasification power generation system, as shown in [Figure 1: see original paper]. Air-dried biomass (with 15% moisture content) and steam are fed into the solar reactor, where concentrated solar energy from the heliostat field at 1000-1500 K is projected onto the gasification reactor to drive the biomass gasification reaction. The high-temperature syngas produced is cooled by a gasification waste heat boiler to recover sensible heat. After cooling and purification, the syngas is sent to the gas-steam combined cycle power generation system. The combined cycle is equipped with a dual-pressure reheat waste heat boiler. Partial preheated saturated water extracted from the waste heat boiler is sent to the gasification waste heat boiler, where it is further heated to superheated steam using the high-temperature sensible heat of the syngas. Part of this steam serves as the gasifying agent for the absorber/reactor, while the remaining superheated steam is returned to the waste heat boiler for further heating before being sent to the steam turbine for power generation.

A reference biomass gasification power generation system was also constructed for comparative analysis with the same biomass input. This reference system employs conventional biomass gasification using oxygen/steam as the gasifying agent (with 95% oxygen purity). The difference between the reference system and the proposed system lies only in the gasification method and parameters. The main equipment parameters under design conditions are listed in .

Note: S/B = Steam/Biomass, the mass ratio of steam to air-dried biomass; ER = Equivalence Ratio, the ratio of actual air consumption to theoretical air required for complete combustion during biomass gasification.

2.2 Performance Evaluation Indicators

The solar-biomass gasification power generation system is evaluated based on the first and second laws of thermodynamics using a specific reference system. The following evaluation indicators are selected:

The solar share fraction f characterizes the proportion of solar energy in the total energy input, as shown in Equation (1).

The syngas chemical energy upgrade coefficient U for the biomass gasification section represents the ratio of syngas chemical energy obtained from solar-biomass gasification to that from the reference system, as shown in Equation (2).

For the solar-biomass gasification power generation system, the overall system performance is evaluated using the system thermal efficiency _I,tot and system exergy efficiency _{II},tot, as shown in Equations (3) and (4). Additionally, the net solar-to-electricity conversion efficiency _{sol}-elec characterizes the ratio of input solar thermal energy converted to electrical power, as shown in Equation (5).

In the equations, n represents syngas molar flow rate (kmol/s); LHV and e denote lower heating value and fuel exergy (kJ/kmol or kJ/kg), respectively; Q_{sol} and E_{sol} represent solar heat collection and solar thermal exergy (kW), calculated as Q_{sol} = Q_{sol},rec/ _{col} and E_{sol} = (Q_{sol},rec/ _{col}) · (1 - T_0/T_{sun}). Subscripts: gas and bio denote syngas and biomass; ref and ch denote reference system and chemical exergy.

3.1 Biomass Gasification Characteristics

The gasification reaction characteristics of solar-biomass gasification were analyzed using the Gibbs free energy minimization model in Aspen Plus process simulation software, as shown in [Figure 2: see original paper]. As the gasification temperature increases, the CO_2 and CH_4 contents in the syngas gradually decrease, with CH_4 content dropping sharply below 1% when the temperature reaches 960 K. Meanwhile, the H_2 and CO contents increase. After the gasification temperature exceeds 1000 K, the H_2 content decreases slightly but remains above 42%, while the growth trend of CO content becomes gradual.

The variation trend of the H_2/CO ratio in syngas is shown in [Figure 3: see original paper]. Due to the rapid increase in CO content, the H_2/CO ratio decreases with increasing gasification temperature. Compared with conventional biomass gasification, the variation trends of H_2/CO ratios from the two different gasification methods are similar. When the gasification temperature exceeds 1000 K, the decreasing trends of H_2/CO ratios for both solar-biomass gasification and conventional gasification become gradual, but the former maintains higher H_2/CO ratios, with differences reaching 0.62–0.76. At gasification temperatures of 1000–1500 K, the H_2/CO ratio of syngas from solar-biomass gasification is 1.65–2.44, making it suitable as high-quality syngas for producing clean liquid fuels such as methanol and dimethyl ether.

During solar-biomass gasification, high-temperature solar energy drives the conversion of solar energy into syngas chemical energy, achieving stable storage and energy quality upgrade. The solar share fraction f and syngas chemical energy upgrade coefficient U of the system vary with gasification temperature, as shown in [Figure 4: see original paper].

Increasing the gasification temperature raises the sensible heat of reactants and reaction enthalpy change, thereby increasing the solar share fraction. At 950 K, the solar share reaches 35.98%, after which its growth rate slows. Meanwhile, the absolute value of syngas chemical energy obtained per unit mass of biomass increases. In conventional biomass gasification, higher temperatures require consuming more biomass to provide reaction heat, which reduces the chemical energy of the produced syngas. Consequently, the upgrade coefficient U increases with temperature. At 950 K, U reaches 1.28, and its growth rate subsequently slows, indicating that the efficiency of solar-to-chemical energy conversion does not continue to increase indefinitely at higher temperatures. Additionally, higher material temperature resistance is required, and comprehensive consideration of thermodynamic performance impacts is necessary.

3.2 Performance Analysis of Solar-Biomass Gasification Power Generation System

The purified and cooled syngas is utilized in the gas-steam combined cycle power generation system, ultimately achieving conversion of solar energy to electricity via syngas chemical energy. Adjusting the biomass gasification temperature is an important means of regulating operational characteristics. Increasing the gasification temperature raises the solar share of total system energy input, which increases the chemical energy of the syngas and ultimately enhances power generation capacity. As shown in [Figure 5: see original paper], increasing the gasification temperature from 1000 K to 1500 K raises the system electrical power output P from 67,354 kW to 73,747 kW, an increase of 9.49%. The net solar-to-electricity conversion efficiency _{sol}-elec of the solar-biomass power generation system increases from 23.20% to 24.20%.

However, it should be noted that although raising the gasification temperature within this range increases solar energy input and syngas chemical energy, the thermal losses in the solar collection and gasification processes also increase.

This causes the overall thermal and exergy efficiencies of the solar-biomass power generation system to decrease from 36.04% and 33.78% to 33.2% and 31.76%, respectively. Excessively high gasification temperatures inevitably increase heat losses from the solar gasification reactor and impose stricter technical requirements on the reactor. Therefore, gasification temperature should not be increased solely to pursue higher power output; optimal operating parameters should be selected based on biomass reaction characteristics and technological considerations.

3.3 System Energy/Exergy Balance Analysis

The solar-biomass gasification power generation system represents a scientific integration of high-temperature solar thermochemical reactors with advanced gas-steam combined cycle power generation. The energy input side consists of two renewable energy sources—biomass and solar—while the system product is high-quality secondary energy: electricity. Through system integration, the thermal and exergy efficiencies of the solar-biomass gasification power generation system reach 34.90% and 33.08% under design conditions. Since the system inputs are only renewable energy sources, despite CO_2 emissions, the specific emission is only 0.568 kg CO_2/kW · h, far below the 0.997 kg CO_2/kW · h of conventional coal-fired power systems. Considering CO_2 reabsorption through photosynthesis, the proposed solar-biomass gasification power generation system is a near-zero CO_2 emission advanced power generation system. Compared with the reference system, the net solar-to-electricity efficiency _{sol}-elec of the proposed system reaches 23.68%, while the biomass fuel savings rate is 25.04% based on the same electricity output benchmark.

To comprehensively analyze system thermodynamic performance, energy and exergy balances were calculated for the proposed system based on the first and second laws of thermodynamics, as shown in . Based on the energy balance analysis, the main thermal losses occur in the steam turbine exhaust condensation process and solar collection process, accounting for 41.91% and 33.2% of total system thermal losses, respectively. Sensible heat loss from syngas and flue gas heat loss account for 10.21% and 9.54%, respectively. For exergy analysis, the exergy loss from the solar collection section is the largest, representing 34.99% of total system exergy losses. Additionally, due to large reaction temperature differences in syngas combustion and biomass gasification processes, the exergy losses in the combustion chamber and biomass gasification reactor reach 21.5% and 18.72%, respectively. Since thermal and exergy losses from the solar collection process represent a relatively high proportion of total losses, optimizing system operating parameters according to gasification reaction requirements is crucial for improving system thermodynamic performance.

Conclusions

To achieve efficient complementary utilization of solar and biomass resources, this paper proposes a method using high-temperature concentrated solar energy as the heat source for biomass gasification, integrated with an advanced gas-steam combined cycle power generation system. Through system simulation and analysis, the following conclusions are drawn:

(1) Utilizing solar energy to drive biomass gasification reactions can convert intermittent and unstable solar energy into syngas chemical energy while avoiding partial biomass oxidation combustion, thereby increasing syngas chemical energy and producing syngas with a higher H_2/CO ratio.

(2) Through system integration, solar energy is converted to and stored in syngas chemical energy, achieving stable and efficient solar energy storage while upgrading its energy grade. The net solar-to-electricity efficiency of the system can reach 23.68%, which is higher than conventional solar thermal power generation efficiency.

(3) Increasing the gasification temperature raises the solar share input to the system, the syngas chemical energy upgrade coefficient, and the system power output. When the gasification temperature increases from 1000 K to 1500 K, the overall thermal and exergy efficiencies decrease from 36.04% and 33.78% to 33.2% and 31.76%, respectively. Therefore, optimal system operating parameters should be selected based on biomass reaction characteristics.

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