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A polygeneration system for the methanol production and the power generation with the solar–biomass thermal gasification ☆

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A B S T R A C T

A polygeneration system of generating methanol and power with the solar thermal gasification of the biomass is proposed in this work. The endothermic reactions of the biomass gasification are driven by the concentrated solar thermal energy in a range of 1000–1500 K. The syngas from the biomass gasification is used to produce the methanol via a synthesis reactor. The un-reacted gas is used for the power generation via a combined cycle power unit. The thermodynamic and economic performances of the polygeneration system are investigated. A portion of the concentrated solar thermal energy can be chemically stored into the syngas, and thus the energy level of the solar thermal energy is improved. Numerical simulations are implemented to evaluate the thermal performances of the proposed polygeneration system. The results indicate that H_2/CO molar ratio of the syngas reaches 1.43–1.89, which satisfies the requirements of the methanol synthesis. The highest energy efficiency and the exergy efficiency of the polygeneration system approximately are 56.09% and 54.86%, respectively. The proposed polygeneration system can achieve the stable utilization of the solar energy and the mitigation of CO_2 emission, and thus a promising approach is introduced for the efficient utilization of the abundant solar and biomass resources in the Western China.

1. Introduction

Fossil energies, including coal and petroleum, are being consumed rapidly, which brings serious environment problem. The limited supply of the fossil energy restricts the sustainable development. In order to address the above challenges, numerous environmental friendly and economical alternative renewable energies, including solar energy and biomass, have attracted increasing attentions [1–3].

The utilization process of the solar energy is clean, and the gross of the solar energy is huge. Solar energy is viewed as an alternative for the alleviation of the current energy and environment concerns. In order to achieve efficient utilization, however, we will face the challenges such as low energy density and intermittent nature.

Similarly, the biomass is a renewable energy consisting of the carbohydrates, and can be utilized by various methods. Compared with other renewable technologies, including solar and wind, the biomass provides a renewable carbon resource, and can produce the biogas and the liquid fuels with CO_2-neutral [4–6]. In particular, the gasification is one of the most important approaches of the utilization of the biomass, which is a thermochemical conversion technology for the production of the syngas (synthesis gas, a mixture composed of H_2 and CO). The syngas can be directly utilized in a Brayton–Rankine combined cycle for the electricity generation [7,8]. Moreover, the syngas also can be converted into various valuable fuels, including H_2 (water–gas shift reaction), diesels (Fischer–Tropsch process) and methanol (synthesis) [9–11].

In conventional biomass gasification technologies, air, oxygen, air–steam or oxygen–steam is chosen as a gasification agent. The conventional gasification is an autothermal reaction process, in which the heat is supplied by the in-situ combustion (oxidation) of the biomass with the air or oxygen. The conventional conversion approaches consist of three main steps: (1) pyrolysis, the biomass is decomposed as tar, gas and char, (2) oxidation, the pyrolysis products and oxygen are reacted and the large amounts of heat are released, (3) gasification, the tar and char are gasified to form the syngas [12].

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Nomenclature

CRF	capital recovery factor
E	exergy (kW)
e	specific exergy (kJ kg^{-1} or kg $kmol^{-1}$)
HHV	high heat value (kJ $kmol^{-1}$ or kJ kg^{-1})
LEC	leveled energy cost ($)
m	mass flow rate (kg s^{-1})
n	molar flow rate (kmol s^{-1})
Q	heat (kW)
S	saving ratio (%)
W	electricity power (kW)
Greek letters	
η	efficiency (%)
Subscript	
I	first law of thermodynamics
II	second law of thermodynamics
bio	biomass
chem	chemical energy
fresh	fresh syngas
gas	produced syngas
O&M	annual operation and maintenance
ref	reference system
solar	solar energy

One of the main advantages of conventional technologies depends mainly on the simplicity of the reaction system. However, the heat resource from the combustion of the biomass accounts for 25–40% of the input biomass, and the syngas that may be contaminated by the combustion byproducts has a low H_2/CO molar ratio. Studies indicate that the high-temperature solar thermochemical technology is a promising solution for the supply of the process heat, in which the biomass gasification can be driven by the concentrated solar energy [13,14].

The concentrated solar energy is used as the high-temperature process heat source rather than the in-situ combustion of the biomass, and thus more biomass feedstock can be efficiently utilized and CO_2 molar fraction in the syngas may be reduced owing to the fact that the biomass combustion process is removed [15]. Moreover, the concentrated solar energy is converted into the chemical energy of the syngas, the heat value of the syngas from per unit of biomass is improved because of the introduction of the additional solar energy, and thus the solar energy is chemically stored in an amount equal to the enthalpy change of the endothermic reactions. This approach is viewed as a promising pathway of producing valuable and low-carbon chemicals from renewable resources [14–17].

The design of the solar thermochemical reactor is challenging, which plays a crucial role in the commercial utilizations of the solar-driven biomass gasification. According to the approaches of heating the feedstock, the solar thermochemical reactors can be classified into two types: directly irradiated reactors and indirectly irradiated reactors. Presently, several solar thermochemical reactors have been developed [18]. Z'Graggen et al. [19] presented a 5 kW cylindrical cavity-receiver prototype reactor. Piatkowski et al. [20,21] described a packed-bed solar reactor, both reactors had been tested with carbonaceous material feedstock, and a higher chemical conversion of the feedstock was obtained and the high-quality syngas was yielded. Gokon et al. [22] designed an internally circulating fluidized bed reactor for CO_2 gasification of the coal coke, which results in a homogeneous gasification reaction for all bed layers and achieves a favorable reaction kinetics.

Additionally, numerous system configurations were developed for the effective utilizations of the syngas. Hertwich and Zhang [23] presented a 3rd biofuel generation process using the concentrated solar energy as a main energy source. Kaniyal and Ng et al. [24,25] developed different multi-function systems for the production of the F–T diesel and electricity based on the solar thermal gasification of the fossil fuel. Ozturk and Dincer [26] proposed a CCHP system by integrating a Brayton–Rankine combined cycle and the PEM fuel cell.

In order to satisfy the demand of the clean liquid fuel like methanol and to improve the utilization efficiency of renewable energies, in this work we propose a solar-driven biomass gasification based a polygeneration system with the outputs of the methanol and power, and the performances of the system are evaluated. The main contributions can be summarized as follows:

(1) A new polygeneration system of generating methanol and power with the solar thermal gasification of the biomass is proposed to simultaneously achieve the stable utilization of solar energy and biomass, the reduction of the consumption of the fossil fuels and the mitigation of CO_2 emission.
(2) The proposed polygeneration system yields the qualified syngas, which is suitable for methanol synthesis. Especially, the water-shift process can be eliminated, and the un-reacted syngas is directly combusted for the power generation. The thermodynamic performance of the new system can be improved.
(3) The thermodynamic properties of the solar-driven biomass gasification process are investigated, and the thermodynamic and economic performances of the polygeneration system are evaluated.
(4) For the proposed system, the in-situ biomass combustion in the process of gasification is avoid, the solar energy can be converted and stored into the chemical energy of the methanol, and thus an effective approach of utilizing the renewable energies is introduced.

According to the main motivation of the work, we organize the rest of this paper as follows. In Section 2, a new polygeneration system is proposed, and the reference systems are determined. In Section 3, the thermodynamic properties of the solar-driven gasification for the biomass sample are investigated. The effects of the gasification temperature and the recycle ratio of the un-reacted syngas on the system thermodynamic performances are evaluated in Section 4. Section 5 appraises the sensitivity of the system economic performances on the price of the biomass and electricity. Finally, Section 6 summarizes the main conclusions.

2. Polygeneration system and the evaluation criterion of the system

2.1. Polygeneration system

Based on the solar-driven steam-based biomass gasification, the produced qualified syngas can be applied to various processing industries. Seeking an efficient utilization of the qualified syngas is highly desired for practical applications. If the syngas is directly used to generate the electricity by means of combustion, the