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Investigation of thermodynamic performances for two solar-biomass hybrid combined cycle power generation systems

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ABSTRACT

Two solar-biomass hybrid combined cycle power generation systems are proposed in this work. The first system employs the thermochemical hybrid routine, in which the biomass gasification is driven by the concentrated solar energy, and the gasified syngas as a solar fuel is utilized in a combined cycle for generating power. The second system adopts the thermal integration concept, and the solar energy is directly used to heat the compressed air in the topping Brayton cycle. The thermodynamic performances of the developed systems are investigated under the on-design and off-design conditions. The advantages of the hybrid utilization technical mode are demonstrated. The solar energy can be converted and stored into the chemical fuel by the solar-biomass gasification, with the net solar-to-fuel efficiency of 61.23% and the net solar share of 19.01% under the specific gasification temperature of 1150 K. Meanwhile, the proposed system with the solar thermochemical routine shows more favorable behaviors, the annual system overall energy efficiency and the solar-to-electric efficiency reach to 29.36% and 18.49%, while the with thermal integration concept of 28.03% and 15.13%, respectively. The comparison work introduces a promising approach for the efficient utilization of the abundant solar and biomass resources in the western China, and realizes the mitigation of CO_2 emission.

1. Introduction

Numerous environmental friendly renewable energies, including solar energy and biomass, have attracted increasing attentions and been viewed as an alternative for the alleviation of the current energy and environment concerns [1–4].

Solar energy is clean and can be used for producing the heat and electricity, the photovoltaic (PV) and concentrated solar power (CSP) technologies have been applied in solar power generation [5–7]. Currently, in the field of the solar thermal utilization, various types of solar collectors, e.g., flat plate collector, parabolic trough collector, solar tower and dish receiver, can be used to produce the solar heat with different temperature levels for satisfying different energy demands [8–10]. However, the inherent properties of the solar energy, like low energy density and intermittence, will affect its thermodynamics and economics behaviors, and restrict the applied scopes. In order to address these issues, the hybrid system concept may be a promising solution, and the drawbacks of the hybridized energies can be compensated by each other [11–15].

Biomass, other types of renewable energy, can be utilized by diverse technologies of combustion, pyrolysis and gasification for directly producing the heat, tar and syngas, respectively. In particular, the gasification is one of the most important approaches for processing biomass, which is a set of endothermic thermochemical conversion reactions for the production of the syngas (a mixture composed of H_2 and CO) [16–18]. Furthermore, the biomass integrated combined cycle system (BIGCC) is developed for efficiently using the gasified syngas, and it also provides a chance to hybrid the solar energy. Whereas, the selection of the solar injection point in the BIGCC system is depended strongly on the solar thermal temperature. Firstly concentrated solar energy can be used to drive the biomass gasification and substitute the feedstock inner combustion process. Additionally, like the solar hybrid natural gas-fired combined cycle, the solar energy can be injected into the topping Brayton cycle of the typical BIGCC system for heating the compressed air and the bottoming Rankine cycle for preheating (or evaporating) the feed water [19–23].

Within the process of the solar-biomass gasification, the concentrated solar energy is used to provide the high-temperature

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Nomenclature

A	heliostat area
f	share fraction
H	enthalpy (kJ mol^{-1} or kJ kg^{-1})
HHV	high heat value (kJ kg^{-1})
LHV	low heat value (kJ kg^{-1})
m	mass flow rate (kg s^{-1})
Q	heat (kW)
W	electric power (kW)

Greek letters

η	efficiency (%)

Subscript

annual	annual accumulated or averaged
ASU	air separation unit
aux	auxiliary devices
bio	biomass
CC	combined cycle
net	net output power
opt	optical
parasitic	parasitic consumption
ref	reference system
solar	solar energy
sol-elec	solar-to-electric
sys	system
th	thermal

process heat resource and then to be converted into the chemical energy of the syngas, which readily chemically stored in an amount equal to the enthalpy change of the endothermic reactions [24–26]. Therefore, the converted solar energy can be efficiently utilized. Additionally, many prototype reactors, such as two-zone solar reactor, fluidized bed reactor have been developed and achieved favorable solar conversion performances through experimental investigations [27–29]. Except for power generation, the solar gasification can also be viewed as a promising pathway of producing valuable liquid fuel of methanol & F-T diesel [30–32]. It is worth noting that biomass is a renewable energy comprising of the carbohydrates with high volatile content, and it has favorable reactivity with the lower reaction temperature compare with other fossil solid energies, like coal, which can promote the wide application of the solar-biomass gasification. Moreover, the hybridized energies are full renewable, and thus the CO_2-neutral can be achieved.

The introduction of the solar heat into gas-fired combined cycle is another promising hybrid way. In particular, Kribus et al. [33] reported a feasibility study for a solar hybridized with the topping cycle, the hybridized solar energy is efficiently converted via heating the compressed air, and a substantial fuel savings and environmental benefits can be achieved. The first prototype solar powered gas turbine system has been tested during 2002 at Plataforma Solar de Almería (PSA) of Spain, the system could be operated at 230 kW_e power to grid without major problems [34,35]. Meanwhile, a high-temperature pressurized-air solar receiver with an annular reticulate porous ceramic foam concentric has been experimentally investigated, and the peak outlet air temperatures exceeding 1200 °C were reached [34–36]. The detailed off-design assessment of the solarized gas turbine and the solarized combined cycle plant configurations have been conducted, and the annual behavior implies that the most valuable advantage of high power generation efficiency is the hybrid solar gas turbine technology [37–40]. Additionally, investigations on the system optimization had been implemented by Segal [41] in terms of the heliostat field and tower, the receiver and its secondary concentrator, and the power block.

The above work shows an industrial feasibility and great potential for the solar-biomass hybrid power generation concept. Whereas, published contributions always individually focus on the mechanism research of solar gasification reaction & solar reactor, or the system assessment of the solar hybrid system according to typical gas-fired combined cycles. Meanwhile, the configuration of the existing solar-biomass hybrid system need to be deeply investigated and optimized. Therefore, the aims of this paper are to propose and assess the novel solar-biomass hybrid power generation systems, and the main contributions can be summarized as follows:

(1) The hybrid utilization concept for renewable energies of solar energy and biomass is propose to achieve stable utilization of the solar energy, the reduction of the consumption of the fossil fuels and the mitigation of CO_2 emission.
(2) Two types of solar-biomass hybrid routines, including thermochemical hybrid and thermal integration concepts, for power generation are developed, the characteristics for each system are compared and discussed.
(3) The thermodynamic properties of the solar-driven biomass gasification process are investigated, and the on-design and off-design performances for the two types power generation are evaluated.

The rest of this paper is organized as follows. In Section 2, we propose two types of solar-biomass hybrid power generation systems, and the system performance evaluation criterions are given. In Section 3, the chemical composition of the biomass sample is determined, and thermodynamic properties of the solar-driven gasification for the biomass sample are investigated. The analysis of the nominal and off-design performances within the representative days and a year period are presented in Section 4. Finally, we summarize the main conclusions in Section 5.

2. System description and performance analysis

2.1. System description

The concentrated solar energy is a kind of thermal energy, and it can be directly used as typical heat resource to drive the heat engine or to drive various types of thermochemical reactions (partly depended on the temperature of solar thermal energy). In this work, the solar-biomass hybrid utilization concept is proposed which integrates with the combined cycle power generation system, the concentrated solar energy can be introduced by the thermochemical and thermal integration routines. Correspondingly, the developed systems with two technical options are depicted in Fig. 1, both the systems are consisted of the biomass gasification subsystem, the solar collection subsystem and the power generation subsystem.

Option I applies a solar thermochemical technical routine, named solar gasification combined cycle system (SGCC system for short). The biomass-steam gasification reaction is carried out,