ARTICLE IN PRESS

Applied Energy xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

New solar-biomass power generation system integrated a two-stage gasifier

Zhang Bai [a,b], Qibin Liu [a,b,*], Jing Lei [c], Hui Hong [a,b], Hongguang Jin [a,b]

[a] Institute of Engineering Thermophysics, Chinese Academy of Sciences, Beijing 100190, PR China
[b] University of Chinese Academy of Sciences, Beijing 100049, PR China
[c] School of Energy, Power and Mechanical Engineering, North China Electric Power University, Beijing 102206, PR China

HIGHLIGHTS

- A new solar-biomass power generation system is proposed.
- Endothermic reactions of the biomass gasification are driven by solar energy.
- The thermodynamic properties of the system are numerically investigated.
- The superiorities of the proposed system are validated.

ARTICLE INFO

Article history:
Received 5 March 2016
Received in revised form 3 June 2016
Accepted 17 June 2016
Available online xxxx

Keywords:
Solar energy
Solar thermochemistry
Two-stage biomass gasification
Power generation
Thermodynamics evaluation

ABSTRACT

A new solar-biomass power generation system that integrates a two-stage gasifier is proposed in this paper. In this system, two different types of solar collectors, concentrating solar thermal energy at different temperature levels, are applied to drive solar-biomass thermochemical processes of pyrolysis (at about 643 K) and gasification (at about 1150 K) for production of solar fuel. The produced solar fuel, namely gasified syngas, is directly utilized by an advanced combined cycle system for power generation. Numerical simulations are implemented to evaluate the on-design and off-design thermodynamic performances of the system. Results indicate that the proposed system can achieve an overall energy efficiency of 27.93% and a net solar-to-electric efficiency of 19.89% under the nominal condition. The proposed two-stage solar-biomass gasification routine exhibits improved system thermodynamic performance compared to that in one-stage gasification technical mode, and the provided heat resource is in a good match with the requirements for the biomass gasification procedure. Under given simulation conditions in this paper, the energy level upgrade ratio in the proposed two-stage solar-biomass gasification system for the introduced solar thermal energy is as high as 32.35% compared to 21.62% in one-stage gasification mode. Meanwhile, the daily average net solar-to-electric efficiency on the representative days reaches to the range of 8.88–19.04%, while that of 9.97–15.71% in one-stage model. The research findings provide a promising approach for efficient utilization of the abundant solar and biomass resources in western China and reduction of CO_2 emission.

1. Introduction

Renewable energies, including solar energy and biomass, contribute to the alleviation of current energy and environment concerns due to the features of clean utilization and abundant storage [1–4].

Various types of solar collectors, including flat plate collector, parabolic trough collector, solar tower and dish receiver, have been developed to concentrate solar energy at different temperature levels [5–8]. Currently concentrating solar power (CSP) technologies have been widely applied to generate power in addition to photovoltaic (PV) technology [9–12]. Thermal energy concentrated by solar collectors is used to heat feed-water to superheated steam directly or through a heat transfer fluid (i.e., synthetic oil or molten salt) and then the superheated steam drives the steam turbine for power generation. Due to the uneven temporal and spatial distribution of solar energy, storage of solar energy using molten salt or other phase change materials are investigated [13–17]. Additionally, an emerging technology in solar thermal utilization use compressed air as heat transfer medium. The first prototype of a

* Corresponding author at: Institute of Engineering Thermophysics, Chinese Academy of Sciences, Beijing 100190, PR China.
E-mail address: qibinliu@mail.etp.ac.cn (Q. Liu).

http://dx.doi.org/10.1016/j.apenergy.2016.06.081
0306-2619/© 2016 Published by Elsevier Ltd.

Nomenclature

A	energy level (pre-exponential factor)
E	exergy (kJ mol^{-1} or kJ kg^{-1})
H	enthalpy (kJ mol^{-1} or kJ kg^{-1})
HHV	high heat value (kJ kg^{-1})
m	mass flow rate (kg s^{-1})
Q	heat (kW)
R	the gas constant (8.314 J/(K mol))
S	heliostat area (m^2)
t	time
T	temperature (K)
W	electric power (kW)
Greek letters	
α	reaction conversion rate
β	heating rate (K min^{-1})
η	efficiency (%)
ϑ	reaction heat factor
Subscript	
ASU	air separation unit
aux	auxiliary devices
bio	biomass
CC	combined cycle
day	daily accumulated or averaged
net	net output power
opt	optical
parasitic	parasitic consumption
ref	reference system
solar	solar energy
sol-elec	solar-to-electric
sys	system
th	thermal

solar powered gas turbine system was tested in 2002 without major problems, and many investigations on the related issues have been conducted subsequently [18–20].

The inherent properties of solar energy, such as low energy density and intermittency, provide difficulty in keeping the thermodynamic and economic performances of the solar devices at a high level. Solar thermochemical utilization is a promising solution to these limitations. Among current solar thermochemical utilization technologies, solar driven biomass gasification has also attracted considerable attention [21,22].

Biomass is another type of renewable energy that can be utilized through chemical reactions such as combustion, pyrolysis and gasification to produce heat, tar and syngas, respectively. In particular, gasification is one of the most important technique for processing biomass. While, in gasification, reaction heat from biomass in-situ combustion is needed to drive a set of endothermic thermochemical conversion reactions for the production of syngas (a mixture composed of H_2 and CO) [23–25]. Therefore, it is possible to introduce solar thermal energy into the thermochemical reaction of biomass gasification in order to achieve more efficient biomass utilization. In the process of solar-biomass gasification, concentrated solar energy is introduced to provide high-temperature heat resource for driving the biomass gasification reaction, in which solar thermal energy, with an amount equal to the enthalpy change of the endothermic reactions, is converted into the chemical energy of the syngas and low-carbon footprint transportation fuels [22]. It is worth mentioning that biomass is composed of carbohydrates with high volatile content and exhibits favorable reactivity. More importantly, the hybridized solar energy and biomass are renewable which contribute to CO_2 emission reduction.

Currently, numerous prototype reactors, such as two-zone solar reactor, fluidized bed reactor, packed-bed reactor, have been developed for solid fuel solar gasification and a favorable solar conversion ratio can be achieved through experimental investigations [26–31]. Additionally, solar gasification acts as a promising pathway for valuable liquid fuels production such as methanol and Fischer–Tropsch diesel, and in some publication, the polygeneration concept is employed to enhance system performance [32–35]. In addition, gasified syngas, as a kind of solar fuel, can be directly utilized for power generation with a favorable efficiency by incorporating with the combined Brayton–Rankine cycle [36].

Biomass gasification process is a set of complex reactions, in which the biomass feedstock is preheated, and then pyrolyzed to yield tar and char, then the tar is cracked and char is gasified with the gasification agent (e.g. CO_2 or steam) to produce non-condensable syngas [37–39]. Generally, the biomass preheat and pyrolysis steps can be implemented under a mid-temperature condition of lower than 673 K. However, most previous publications only used point focus collectors to concentrate high-temperature thermal energy to drive the gasification process, which has a relatively high energy loss and capital investment compared to low-temperature line focus collectors such as parabolic collectors, and more exergy loss due to higher temperature difference between solar energy source and biomass preheat and pyrolysis chemical reaction.

Therefore, the thermal heat resources should be introduced correspondingly to the individual temperature requirement of each reaction procedure. A two-stage gasification concept, i.e., using high-temperature heat resource to drive the biomass gasification, mid-temperature solar thermal energy for biomass preheating and pyrolysis procedures, is an effective solution. Naturally, the main objectives of this work include proposing a two-stage solar-biomass gasification concept, developing a novel solar-biomass hybrid power generation system, and assessing performances of the solar thermochemical conversion process and the developed system. The main contributions are summarized as follows:

(1) A novel hybrid power generation system integrated with a two-stage solar-biomass gasification process is proposed for effective utilization of solar energy and biomass. The proposed system reduces fossil fuel consumption and mitigates CO_2 emission.
(2) In the proposed system, two solar collection devices are employed to provide concentrated solar thermal energy at different temperatures. In addition, the pyrolysis and gasification of the biomass feedstock are driven by concentrated solar thermal energy at appropriate temperature. In this method, exergy destruction in solar collection and thermochemical conversion processes can be reduced.
(3) Solar thermal energy can be converted into chemical energy stored in syngas through solar-biomass gasification. The energy level of the introduced solar energy is upgraded. An effective integrated utilization of the renewable energies can be achieved. In addition, under both design and off-design working conditions, more favorable thermodynamics performances of the proposed system are obtained.

The rest of this study is organized as follows. In Section 2, we propose a novel solar-biomass power generation system integrates

Please cite this article in press as: Bai Z et al. New solar-biomass power generation system integrated a two-stage gasifier. Appl Energy (2016), http://dx.doi.org/10.1016/j.apenergy.2016.06.081