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Energy, exergy and environmental analysis of a hybrid combined cooling heating and power system utilizing biomass and solar energy

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ABSTRACT

A hybrid combined cooling heating and power (CCHP) system driven by biomass and solar energy is proposed, and their complementarity to enhance the system's energy efficiency is analyzed and shown. The CCHP system is primarily composed of a biomass gasification sub-system, solar evacuated collector, internal combustion engine and dual-source powered mixed-effect absorption chiller. The product gas produced by the gasifier drives the internal combustion engine to generate power, and the waste heat after generation is utilized to produce cooling and heating with the collected heat from the solar collectors. Under the design conditions, the thermodynamic performances under variable external conditions and energy ratios are investigated and analyzed. The results indicate that the primary energy ratio and the exergy efficiency are 57.9% and 16.1%, respectively, and the carbon emission reduction ratio is about 95.7%, at the design condition. The complementarity analysis between the biomass and solar energy shows that the biomass subsystem makes a greater contribution to the total system primary energy ratio and exergy efficiency than the contributions from the solar subsystem, and the participation of solar energy is conducive to the system emission reduction.

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1. Introduction

Distributed energy systems (DES) are becoming one of the more attractive options worldwide because of their high overall efficiency, low greenhouse gas emissions, high reliability and other features [1]. A DES, which includes combined heating and power (CHP) system, combined cooling, heating and power (CCHP) system, and distributed renewable energy technologies can realize a cascading utilization of energy. The advance and development of DES has promoted various studies on their technology [2], system configuration [3,4], performance evaluation [5], and optimization [6,7], and most of the studies have concentrated on establishing optimal DES to achieve favorable costs, energy savings and emission reductions.

In particular, renewable energy resources are sustainable alternatives to natural gas for driving traditional CHP/CCHP systems [8], which has gradually become a topic of intense study. Focusing on the energy sources in DES, hybrid DES combine renewable energy resources and fossil resources to decrease greenhouse gas emissions and simultaneously accommodate instabilities in renewable energy. The literature on hybrid DES discusses different forms of complementary energy, for example hybrid wind/photovoltaic energy systems [9], multicomponent systems, including photovoltaic panels, wind generators and biomass gasification plants [10], hybrid geothermal-solar systems [11], hybrid solar and chemical looping combustion systems [12], CCHP systems based on co-firing natural and biomass gasification gases [13], solar-biomass hybrid air-conditioning systems [14] and hybrid polygeneration systems that utilize biomass fuel and solar power [15].

Among the renewable energy resources, biomass and solar energy currently have attracted considerable attention from academics and researchers for their green environmental protection and inexhaustibility advantages. Moreover, biomass is a stable energy resource that can produce continuous power and simultaneously reduce carbon dioxide (CO_2) emissions. To date, only a few studies have been conducted to explore hybrid system driven by biomass and solar energy, especially in terms of analyzing the hybrid proportion of energy resources and showing how they can provide complementary sources of energy. Wang et al. [13] analyzed the influence of different mixture ratios of natural gas and biogas on thermodynamic performance and exergoeconomic cost and discussed the complementary performances of biomass and natural gas. Hashim et al. [16] used the concept of an IBS (Integrated Biomass Solar) town and developed a hybrid solar and biomass plant, which, however, focused on the complementarity of

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Nomenclature

CCHP	combined cooling heating and power
CHP	combined heating and power
COP	coefficient of performance
CO_2	carbon dioxide
DES	distributed energy system
HHV	higher heating value
HX	heat exchanger
IBS	integrated biomass solar
ICE	internal combustion engine
LHV	lower heating value
RMSE	root mean square error

Symbols

A	area (m^2)
E	electricity (kW)
EX	exergy (kW)
HHV	higher heating value (MJ kg^{-1} or MJ Nm^{-3})
LHV	lower heating value (MJ kg^{-1} or MJ Nm^{-3})
$\dot{m}$	mass flow rate (kg/s)
P	pressure (kPa)
Q	energy(kW)
T	temperature (K)
z	mass fraction (dimensionless)
η	efficiency

Subscripts

b	biomass
bio	biomass
c	cooling
ch	chemical
e	electricity
ee	energy
ex	exergy
exh	exhaust
f	fuel
h	heating
hw	hot water
jw	jacket water
n	nominal
p	pump
s	solar
sol	solar
w	water
rw	refrigeration water
v	variable

the electrical supply rather than a system thermodynamics analysis. Academics and specialists have conducted a variety of relevant solar and biomass energy research, including the optimal design of a hybrid solar-assisted biomass energy system for heating [17], a hybrid solar and biomass energy complementary system for power generation [18], a hybrid solar and chemical looping combustion system for solar thermal energy storage [12] and a study of a hybrid solar-biomass air-conditioning system for cooling [14]. However, that research has primarily focused only on particular energy supply products and rarely concentrated on the combined supply of cooling, heating and power. Based on those considerations, the present study is motivated to explore this issue.

The main aim of this work is to propose a hybrid CCHP system that is driven by biomass and solar energy and to explore the complementarity of biomass and solar energy on the energy efficiency. Four complementary conditions are discussed, variable solar irradiation, variable power loads, variable biomass input and variable solar energy input. The first two conditions are studied under single variable, respectively, and the subsequent two variables are conducted simultaneously to analyze all combinations of biomass and solar energy input. In addition, to evaluate the specific influences of biomass and solar subsystems, we propose the concept of subsystem contribution in energy efficiency. Therefore, thermodynamic models of a hybrid CCHP system were constructed and validated; those models used existing technologies of solar heat collection, biomass gasification, absorption refrigeration and power generation. Performances under varying operating conditions were then analyzed, and the system thermodynamic performance, including the primary energy ratios and exergy efficiencies under different energy proportions are discussed to determine the energy efficiency enhancement mechanism in the hybrid CCHP system. The hybrid CCHP system offers several advantageous features, including (1) combined two kinds of renewable energy which was environmentally friendly, (2) reduced the consumption of fossil energy, (3) revealed the complementarity of biomass and solar energy that benefit for the system optimization. This hybrid CCHP system can be innovatory in combined application of biomass and solar energy, especially suitable for remote areas where there are sufficient crops and solar energy.

2. System description

The flowchart of a hybrid CCHP system driven by biomass and solar energy is shown in Fig. 1; the system is composed of a biomass gasification subsystem, solar photothermal collection subsystem, internal combustion engine (ICE) power subsystem and waste heat utilization subsystem. Biomass material is first gasified in the downdraft gasifier, and then its product gas is sent to be further cooled in cyclone and purified in spray scrubbers, respectively. Subsequently, the product gas fuel drives the ICE to generate power. During this process, the heat exchanger (HX-01) is employed to recover the sensible heat from the product gas exiting the gasifier to produce domestic hot water. The solar evacuated collectors are used to collect solar photothermal energy to produce mesothermal hot water, the outlet temperature of which is designed to match the outlet temperature of the jacket water from the ICE at approximately 85 °C.

The mixture of jacket water and solar hot water cooperates with the exhaust gas from the ICE, which has a temperature of approximately 460 °C, is fed to a dual-source powered mixed-effect LiBr-H_2O absorption chiller to produce chilled water. After releasing heat in absorption chiller, the outlet exhaust gas still has a temperature of approximately 170 °C, and the heat exchanger (HX-02) is therefore used to recover the waste heat to preheat the cool water. Regarding the hot water part, the outlet temperature, which is approximately 70 °C, is split into two streams that return to the collector and jacket, respectively, for the next cycle. Moreover, when the temperature of the cooled jacket water cannot meet the requirement on engine cooling, it can be further cooled in cooling tower 01.

Consequently, the system creates three products: electricity, chilled water and hot water. Furthermore, the absorption chiller can be used as a heat exchanger to produce hot water, and two products, electricity and hot water, are generated. For later analysis, the base design parameters are shown in Table 1.

3. Thermodynamic model

The thermodynamic models (biomass gasification, ICE, solar evacuated collectors, dual-source absorption chiller and heat

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