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Proposal and research on a combined heating and power system integrating biomass partial gasification with ground source heat pump

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ABSTRACT

Biomass and geothermal energy are becoming promising traditional energy alternatives. For biomass utilization with thermal-chemical gasification technologies, adopting total gasification scheme always leads to large exergy destruction and low thermal efficiency. Besides that, in typical biomass based combined heating and power systems, the flue gas at middle temperature is usually utilized to produce domestic hot water directly, which also leads to large exergy loss for relative large energy grade difference. In the light of geothermal energy utilization, i.e. ground source heat pump systems, for the relative high temperature required of output stream, a relative high compression ratio is required accordingly, which leads to a low coefficient of performance of ground source heat pump. In order to solve the above referred problems, a novel heating and power co-generation system coupling biomass partial gasification and ground source heat pump is proposed and analyzed in this study. The proposed system consists of four subsystems: biomass partial gasification subsystem; gas turbine power generation subsystem; steam turbine power generation subsystems; and ground source heat pump subsystem. The features of this novel system focus on: only part of the biomass is gasified not all (partial gasification), the syngas and unreacted char are used as fuels for gas turbine (Brayton cycle) and steam turbine (Rankine cycle) power generation respectively; in the ground source heat pump subsystem, the temperature of required water is reduced to 39 °C instead of 55 °C, and will be further reheated to 55 °C by flue gas at middle temperature from biomass based combined heating and power subsystem. The thermodynamic performance of the proposed system is numerically investigated. The results indicate that the proposed system can make a better use of biomass and geothermal energy, which can achieve an overall energy efficiency of 72.12% with a heat to power ratio 3.93, and the coefficient of performance of ground source heat pump subsystem can be improved to 5.6 with the compression ratio 3.2. What's more, the system integrating mechanism in this study is very helpful for other advanced biomass based and multi-energy coupling systems.

1. Introduction

Currently, renewable energy resources are becoming alternative options due to their special advantages; especially biomass and geothermal energy have drawn increasingly attention in the worldwide for their abundant and widely distributed features. The biomass has its unique advantage compared with other hydrocarbon energy resources, which can be called CO_2 neutral [1]. The CO_2 released by biomass combustion can be absorbed from the atmosphere to the plants, therefore the net addition of CO_2 released to atmosphere is considered to be zero [2]. Up to now, there are various of technologies for biomass utilization, e.g., Okasha et al. [3] carried out an experimental study on co-combustion of rice straw and natural gas in the fluidized bed, Liu et al. [4] presented a two solar-biomass hybrid combined cycle power generation system, in which the biomass-steam gasification reaction is driven by solar energy, Bach and Chen [5] tested various kinetic models to fit the experimental pyrolysis data, which contributes to find out the optimal pyrolysis model of microalgal biomass, Li et al. [6] investigated the feasibility of a novel system based on anaerobic digestion and biomass gasification, the new concept can produce more biomethane and improve the exergy efficiency. Besides, Basu referred to some other conversion technologies, such as liquifaction and fermentation [7]. Similarly, geothermal energy is also widely accepted and applied, which is stored in the Earth's interior with four types: hydrothermal, geo-pressured, hot rock and dry rock [8]. The significant feature of geothermal energy is its 24 h availability, which is called base load energy resource

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Nomenclature

Abbreviation

CCHP	combined cooling, heating and power
CCR	carbon conversion ratio
CGE	cold gas efficiency
CHP	combined heating and power
COP	coefficient of performance
ER	equivalence ratio
GCU	gas conditioning unit
HHV	higher heating value
HM	homogenerous model
HP	heat pump
HX	heat exchanger
LHV	lower heating value
ORC	organic rankine cycle
RPM	random pore model
SBR	steam/biomass ratio
SCM	shrinking core model

Symbols

A	apparent pre-exponential constant (s^{-1})
$A_{c/e}$	heat transfer areas of condenser or evaporator (m^2)
c	specific heat capacity (kJ/(kmol K))
E	activation energy (kJ/mol)
EX	exergy (kW)
h	specific enthalpy (kJ mol)
HHV	higher heating value (MJ/N m^3)
K	heat transfer coefficient W/(m^2 K)
k	kinetics reaction constant
LHV	lower heating value (MJ/N m^3)
m	mass flow rate (kg/h)
n	polytropic exponent
P	pressure (Pa)
q/Q	heat (kW)
R	universal gas constant (kJ/kmol K)
s	specific entropy (kJ mol)
T	temperature (°C)
t	time (min)
V	volume flow rate (N m^3/h)
w/W	electricity (kW)
Z	percentage (%)
β	multiplication factor
η	efficiency (%)

Subscripts

b	biomass
C	carbon
c	condenser
ch	chemical
dest	destruction
e	evaporator
g	gas turbine
k	element (k)
ph	physical
rc	refrigerant compressor
s	steam turbine

[9]. Therefore, it is not dependent on the weather conditions compared with solar energy [10].

For the development of energy systems, distributed energy system has attracted an increasing attention due to high energy efficiency, low greenhouse gas emission, high reliability and product diversification, etc. [11]. The development of distributed energy system has become a basic consensus among many countries [12]. There are many configurations of distributed energy system depending on the products [13], e.g. combined cooling, heating and power (CCHP) system, combined heating and power (CHP) system. Jradi and Riffat [14] and Deng et al. [15] have reviewed the related technologies, not only the system configurations but also relevant operating strategies.

Some advanced CCHP or CHP systems taking renewable energy resources as primary energy input have been suggested and investigated [16]. Mohammadi et al. [17] suggested and analyzed a CCHP system, which coupling wind energy and compressed air energy storage system, and the research results shown that, the highest exergy destruction occurs in wind turbine, combustion chamber and compress air storage system. Wang et al. [18] carried out a thermodynamic and exergoeconomic analysis of CCHP system co-fired by biomass gasification gas and natural gas, and obtained that the energy and exergy efficiency can be increased by 9.5% and 13.7% respectively with mixing ratio from 0 to 1.0. Calise et al. [19] simulated and optimized a novel solar trigeneration system, which consists of photovoltaic/thermal collectors, solar thermal storage system and reversible water-to-water heat pump. The results showed that the collector area is a key factor for maximum system economic profitability. Kang et al. [20,21] proposed a CHP-GSHP coupling system according to the novel utilization approach of waste heat with mid-low temperature, both the whole system efficiency and COP of the GSHP are improved largely. Besides the systems taking only one kind renewable energy resource as input, many hybrid renewable energy systems occurred and were investigated. Bai et al. [22] proposed a new hybrid power generation system combined with a two-stage solar-biomass gasification process, which adopted two different solar collectors in order to match the heat requirements of biomass gasification. And the on/off design thermodynamic properties were studied, the proposed system showed certain advantages compared with the one-stage gasification mode. Soheyli et al. [23] presented and optimized a novel CCHP system based on PV modules, wind turbines and solid oxide fuel cells. The following electrical load and following thermal load operation strategies were adopted to decrease the extra production, and the co-constrained multi objective particle swarm optimization algorithm was applied for the optimization of components and penalty factors. Moreover, the feasibility of proposed system was validated by a case study. Tempesti et al. [24] studied and compared two novel CHP-ORC systems taking solar and geothermal energy as co-feeds in terms of thermodynamic analysis, different types of working fluids were also investigated in the proposed systems. In a further study, Tempesti and Fiaschi [25] presented the thermo-economic assessment of the CHP-ORC system considering three different working fluids, which concluded that the fluid R245fa was the optimal selection.

For the hybrid systems taking geothermal and biomass as co-feeds, some studies are also investigated. Østergaard et al. [26] demonstrated the feasibility of 100% renewable energy scenario for Aalborg Municipality, which combined the geothermal energy, wind power and biomass. Moret et al. [27] employed and modeled an urban energy system integrating deep geothermal energy and woody biomass through a multi-period Mixed-Integer Linear Programming (MILP) model. A case study in the city of Lausanne, Switzerland was applied to illustrate the above methodology. In addition, Malik et al. [28] proposed a specified multi-generation system based on biomass and geothermal energy. The proposed system consists of seven parts: a biomass combustion cycle, an organic Rankine cycle, an absorption chiller cycle, a Linde