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Evaluation of a combined cooling, heating, and power system based on biomass gasification in different climate zones in the U.S.

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ABSTRACT

A combined cooling, heating, and power system based on biomass gasification is modeled via experiment and its performance is evaluated. The system operation is simulated using load data of small offices located in different climate zones in the U.S. The operation strategy comprises following the electric load (FEL) and following the thermal load (FTL). Based on the operation data, energetic, economic, environmental, and overall performances of the system are evaluated. Results show that the annual integrated performance (S_{whole}) of the system ranges from 0.229 to 0.473 in FEL mode and from 0.067 to 0.457 in FTL mode, in different regions. The system has a better performance in FEL mode, and is more attractive to install in the regions with more thermal load. Furthermore, the match degree of heat to power ratio between load and output also has an effect on the system performance. Sensitivity analysis shows that the system performance is more sensitive to the cost of biomass, cost of grid electricity and CO_2 emission rate of the grid in both modes, and *COP* of thermally activated chiller in FTL mode. By changing the above-mentioned parameters, S_{whole} can be improved by up to 13.7%, 8.2%, 11.0%, and 19.7% respectively.

1. Introduction

In recent years, the aggravation of energy crisis and greenhouse effect has increased the interest on renewable energy. Biomass is one of the foci of renewable energy sources. Because of the features of renewability in nature, wide spread availability and neutrality in relation to global warming [1], biomass energy has enormous potential in reducing fossil fuel consumption and greenhouse gas (GHG) emission. Furthermore, the power production using biomass energy can be continuous and unaffected by the weather, which provides reliability to the power system.

Biomass gasification is a widely used technology for providing a more efficient and cleaner method of power generation. Through gasification, biomass is converted into gaseous fuel, called syngas, which is easier to purify and is more applicable to prime movers [1–3]. Hernández et al. [4] carried out experiments on a diesel engine with partial replacement of biomass gasification gas. With the increase in fuel replacement, particulate emissions decreased significantly and NO_x emissions decreased slightly at all loads and exhaust gas recirculation ratios. Raman et al. [5] designed and developed a power generation system of 75 kWe based on biomass gasification. The energy conversion efficiency and specific fuel consumption were found to be 18% and 1.18 kg/kWh, respectively. The performance of a biomass gasification-based power plant is affected by multiple factors, including parameters of the gasification system [6] and the configurations of the entire system [7]. Therefore, studies have been conducted to optimize the system in the following two aspects.

One is to improve the system by enhancing the efficiency of gasification. Chen et al. [8] studied a power generation system based on supercritical water gasification of coal with partial heat recovery. By utilizing the sensible and latent heat, the efficiency of the system could reach 42.18% when the coal–water slurry concentration was 11.3% and the characteristic temperature was 250 °C. Yan and He [9] investigated a power generation system based on co-gasification of biomass and coal. It was found that the maximum exergy loss occurred in the steam turbine. The energy and exergy efficiency of the system could reach up to 50% and 47%, respectively. Perma et al. [10] focused on the gasification medium. By using renewable hydrogen as gasification medium, the heating value of the produced syngas is improved substantially. As a result,

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Nomenclature

A	area (m^2)
AFR	stoichiometric air fuel ratio (–)
$\bar{c}$	mean specific heat ($kJ \cdot kg^{-1} \cdot K^{-1}$)
CCHP	combined cooling, heating, and power
cer	CO_2 emission rate (kg CO_2-eq/kg or kg CO_2-eq/kWh or kg CO_2-eq/Nm^3)
COP	coefficient of performance (–)
COST	specific cost (\$/kg or \$/kWh or \$/Nm^3)
$\dot{E}$	power (kW)
FEL	following the electric load
FESR	fossil energy saving ratio (–)
FTL	following the thermal load
h	coefficient of convective heat transfer ($W \cdot m^{-2} \cdot K^{-1}$)
Δh_{vap}	latent heat of vaporization (kJ/kg)
HPR	heat to power ratio (–)
GHG	greenhouse gas
ICE	internal combustion engine
LHV	lower heating value (MJ/kg or kWh/Nm^3)
$\dot{m}$	mass flow rate (kg/h or kg/s)
NG	natural gas
OCRR	operation cost reduction ratio (–)
PGU	power generation unit
q	thermal power (kW)
RMSE	root mean square error (unit of the measured variable)
RH	relative humidity (–)
S_{whole}	the integrated performance (–)
SAC	single-effect absorption chiller
T	temperature (K or °C)
$\dot{V}$	volume flow rate (m^3/h or m^3/s)
w	moisture (–)

subscripts

amb	ambient
c	space cooling
con	conventional system
demand	demand of waste heat
el	electricity or electric
exh	exhaust gas
f	feedstock
gen	power generation
grid	public grid
h	space heating
hw	hot water
inf	infiltration
jw	jacket water
latent	latent heat
load	power load
max	maximum
min	minimum
NG	heating appliance fueled by natural gas
original	the original value
rec	recovery of waste heat
s	syngas
sys	system
sensible	sensible heat
th	thermal
tr	power transmission
z	zone

Greek symbols

η	efficiency
λ	excess air coefficient
ρ	density (kg/m^3)

compared with the system based on conventional gasification, the electricity efficiency was improved by 16%–23%. Bai et al. [11] proposed a novel solar–biomass power generation system integrating a two-stage gasifier. It was found that the energy level upgrade ratio of the system achieved as high as 32.35%, comparing to 21.62% in one-stage gasification mode.

Meanwhile, for a power generation system based on biomass gasification, there is a great potential of waste heat utilization [12–13]. Therefore, it is important to efficiently use the waste heat of the system by establishing a combined cooling, heating, and power (CCHP) system. Studies were conducted on the performance evaluation of CCHP systems on multiple aspects. Wang et al. [14] performed energy and exergy analyses of a CCHP system based on biomass air gasification. The energy and exergy loss of each unit was analyzed and compared. It was found that in summer, winter, and transient seasons, the energy and exergy efficiency could reach 50.00%/6.23%, 37.77%/12.51%, and 36.95%/13.79%, respectively. Perna et al. [15] proposed a cogeneration system based on conventional and biomass gasification power plant. The system was modeled and assessed. It was indicated that the system would have better performance if the syngas were applied in a solid oxide fuel cellsystem. Puig-Arnavat et al. [16] modeled and compared different CCHP configurations. It was concluded that the system with all configurations in that article could all be considered as "high-efficiency systems".

In addition to analyzing the effects of a single unit and configuration of the entire system, some researchers observed that the lower heating value (*LHV*) of syngas is extremely low (5–5.9 MJ/m^3 for syngas from wood gasification [17]), which becomes a hindrance of gasification-based power plants [18,19]. Therefore, optimizing the system by improving the quality of input gas is necessary. Li et al. [20] compared the influence of LPG addition on different biomass-derived fuel gas. It was concluded that LPG addition was mostly effective on biomass gasification gas. The energy efficiency, exergy efficiency, energy saving ratio, and CO_2 emission reduction ratio could be improved by up to 7.4%, 5.1%, 17.8%, and 49.2%, respectively. Gao et al. [21] assessed a CCHP system when compositions of the biomass-derived gas were changed. It was confirmed an increase in *LHV* of fuel gas could evidently improve the thermodynamic performance of the CCHP system. Wang et al. [22] modeled and evaluated a CCHP system based on co-firing of natural gas (NG) and gasification gas. The performance of the system to generate 100 kW power was analyzed when the mixing ratio was changed. The energy and exergy efficiency of the system improved from 70.0% to 79.5% and from 21.9% to 35.6%, respectively, when the volumetric fraction of NG was changed from 0 to 1.

The CCHP system is also a demand-side dominated system [23]. In practice, because there is always a gap between energy generations and building loads, auxiliary energy is always required and excess energy is unavoidable [24]. Climatic conditions have a great effect on the performance of the system because they determine the thermal loads for space cooling and heating. Wang et al. [25] evaluated the performance of a CCHP system in different climate