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Thermodynamic performance of a hybrid power generation system using biomass gasification and concentrated solar thermal processes ☆

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HIGHLIGHTS

- A hybrid power generation based on biomass gasification and concentrated solar thermal.
- Investigation of optimal integration by pinch analysis.
- Improvement of system efficiency by co-utilizing surplus heat and solar thermal.
- Efficiency affected by composition and temperature of gasifying agent.

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ABSTRACT

This paper describes the investigation of a hybrid power production system from biomass and solar energy. This paper suggests integration through heat exchanger network as a useful approach to obtain the synergy between biomass and solar. Biomass is first gasified in a bubbling fluidized bed (BFB) gasifier, and then syngas is used in a gas turbine. Excess heat exists in this sub-system and concentrated solar thermal process (CSTP) while there is a demand of steam for generating gasifying agent. Steam Rankine cycle exploits the heat created by these thermal streams to generate power while satisfying the steam demands. Thermodynamic performance was analyzed by process modelling with a semi-kinetic model of BFB gasifier and pinch analyses. The composition and temperature of gasifying agent showed some effect on the overall efficiency of the system. Higher overall efficiency of the system was achieved at higher temperature and higher O_2 fraction in the O_2-steam mixture as gasifying agent. The increase in thermal input from CSTP had positive effect on overall efficiency of the hybrid system until thermal input from CSTP becomes dominant against thermal stream related to the gasifier and the gas turbine.

1. Introduction

Diversifying the portfolio of energy sources is an important issue in order to ensure energy security. Especially, alternative energy of fossil fuel and nuclear energy is required to reduce the risk against fossil fuel depletion and nuclear accident. Power generation with biomass gasification (b-IGCC, biomass-based integrated gasification combined cycle) is one of such alternative technologies, whose output is not affected by the weather conditions like other renewable energies. However, it is still necessary to improve the efficiency to generate electricity from biomass. There is a common strategy to increase the performance of energy plant by integrating two or more processes where heat supplies and demand exist [1]. This paper addresses how the overall performance will be improved when b-IGCC is integrated with concentrated solar thermal processes (CSTP). Gasification is a process that breaks down biomass into smaller molecules to generate syngas, mainly H_2, CO, CO_2, H_2O and CH_4, with the help of heat and oxidizer (so-called gasifying agents). Some gasification processes

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Nomenclature

C	gas concentration (kmol m^{-3})
Cp	specific heat (kJ kg^{-1} K^{-1})
d	diameter (m)
D_e	effective diffusivity (m^2 s^{-1})
E_a	activation energy (kJ mol^{-1})
F	molar flow rate (k mol s^{-1})
h	enthalpy (kJ kg^{-1})
k_o	pre-exponential factor (–)
k'''	rate constant with respect to char volume ((m^3-gas)^n (kmol)$^{1-n}$ (m^3-char)$^{-1}$ s^{-1})
K_e	equilibrium constant (–)
LHV	lower heating value (kJ kg^{-1})
$\dot{m}$	mass flow rate (kg s^{-1})
M	molecular weight (kg kmol^{-1})
M_T	Thiele module (–)
n	reaction order (–)
p	pressure (bar)
P	power (MW)
$P_{el,m}$	marginal power output (MW)
Q_{CSTP}	thermal input from CSTP (MW)
r	reaction rate (kmol m^{-3} s^{-1})
R	ideal gas constant (kJ kmol^{-1} K^{-1})
t	time (s)
T	temperature (K)
V	volume (m^3)
ν_i	stoichiometric coefficient of specie i (–)
X	char conversion (–)

Greek letters

η_{adia}	adiabatic efficiency of the gasifier (–)
$\eta_{el,m}$	marginal electric efficiency (–)
η_{dif}	effectiveness factor of char gasification (–)
ρ	density (kg m^{-3})

Subscripts

b	biomass
c	carbon
char	char
daf	dry and ash free
i	specie i
in	inlet
j	reaction j
out	outlet
pyro	pyrolysis

require heat input to generate steam as gasifying agent or to preheat gasifying agents in order to increase the syngas energy. This means that the integration with other processes that have excess amount of heat may improve the performance of the overall system.

Several concentrated solar power stations (CSP) have started commercial operation in the last decade [2]. Solar radiation is concentrated and stored in a heat transfer fluid (HTF) either with line-focusing (parabolic trough and linear Fresnel) or point-focusing (parabolic dish and heliostats) devices. The temperature of the HTF from a receiver is typically 150–500 °C for line-focusing devices and 500–1500 °C for point-focusing devices, making it attractive for hybrid power generation schemes [3–8]. Dependent on the HTF temperature, concentrated solar energy can be converted into electricity in various power cycles [9,10]: e.g. organic Rankine cycle (ORC) for 0–250 °C, steam Rankine cycle for 250–600 °C, Stirling engines for 600–850 °C, and gas turbines for 850–1500 °C. Nonetheless, steam Rankine cycle is the dominant power generation cycle in commercial-scale CSP plants. Thermal energy storages (TES) are often employed to compensate hourly intermittent of the CSP system. Different forms of TES have been studied, broadly classified as sensible heat storages (such as molten-salt, concrete, ceramics) and latent heat storages (PCM, phase change material) or a combination of both [11–19].

Hybridization is also an important strategy for realizing solar thermal power plant since electricity production cost of stand-alone CSP plants is higher than other sources, typically above 210 USD/MWh$_e$ [20]. Three major approaches are found in the literature, namely hybrid solar-gas turbine (HSGT) system, solar CSP-biomass hybrid system, and solar-assisted biomass gasification. Concentrated solar thermal processes (CSTP) are supplemented to natural gas fired gas turbine in HSGT [3,5,7–9], typically to preheat the compressed air to 850–950 °C prior to combustors. However, the commercial application of this system is limited due to the physical locations of the receiver (top of the tower) and the combustor (on the ground) [7]. Other example of HSGT configuration is to inject steam from CSP system into the gas turbine [5].

Solar CSP–biomass hybrid systems for power production are gaining interest [21] as CO_2-neutral power generation. The concept of hybrid biomass–fired boiler and CSP is discussed in [22], where the biomass boiler is used to accommodate the change in the intensity of solar radiation. Similar principle, tri-generation (production shift among electricity, heat and cooling), was also investigated at small-scale (2–10 MW$_{th}$) hybrid solar-biomass boiler [23]. Several studies [24–30] also focused on using the thermal energy from CSTP to supply energy demand of biomass gasification process. Such configurations boost the yield of syngas and the conversion efficiency of the gasification step. However, the operational instability due to the intermittent solar radiation may overcomplicate process control.

An alternative approach is to hybridize b-IGCC–CSTP through heat exchanger network (HEN), which is the focus of this study. An important aspect of our hybrid b-IGCC–CSTP system is continuous operation of the b-IGCC independent of solar radiation because the hybridization is limited to less-crucial sections, in this case the HEN. Such configurations may enjoy the improvement in energy efficiency while avoiding process control issues. In such system, electricity production of biomass origin virtually plays the role as base-load, and electricity production of solar origin and efficiency improvement by synergy effect plays the role as peak load. It is reasonable because the peak load of electricity in the area with high solar radiation often coincide with the ambient temperature, thus solar radiation. If it is not the case, CSTP can be still used as temporary energy storage since it can store heat in molten salts as most CSP plants can be operated even during cloudy period or night time. It was reported that commercial CSP plant, Gemesolar, achieved 24 h of uninterrupted electricity production [2].

This study presents the investigation of the optimum way to integrate CSTP with b-IGCC for power production, and its thermodynamic performance by process simulation. We assumed that the new system will utilize a bubbling fluidized bed (BFB) gasifier and CSTP with molten salt heat storage system. An accurate model of the BFB gasifier is important because its behavior significantly affects the performance of the whole system. Therefore, we first

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