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Thermodynamic analyses of a biomass–coal co-gasification power generation system

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HIGHLIGHTS

- A biomass–coal co-gasification based power generation system is setup with Aspen Plus.
- Energy and exergy balance calculations are done for this system.
- Sensitivity analysis is done to understand the system operation characteristics.
- Total energy and exergy efficiencies of this system can be 39.9% and 37.6%, respectively.
- About 96.0% of the carbon contained in coal and biomass can be captured in this system.

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ABSTRACT

A novel chemical looping power generation system is presented based on the biomass–coal co-gasification with steam. The effects of different key operation parameters including biomass mass fraction (R_b), steam to carbon mole ratio (R_{sc}), gasification temperature (T_g) and iron to fuel mole ratio (R_{if}) on the system performances like energy efficiency (η_e), total energy efficiency (η_{te}), exergy efficiency (η_{ex}), total exergy efficiency (η_{tex}) and carbon capture rate (η_{cc}) are analyzed. A benchmark condition is set, under which η_{te}, η_{tex} and η_{cc} are found to be 39.9%, 37.6% and 96.0%, respectively. Furthermore, detailed energy Sankey diagram and exergy Grassmann diagram are drawn for the entire system operating under the benchmark condition. The energy and exergy efficiencies of the units composing the system are also predicted.

1. Introduction

Coal is the most important but dirtiest fossil fuel on earth. It is not renewable and can be exhausted one day in the future (U.S. Energy Information Administration, 2013; Franco and Diaz, 2009). In comparison, biomass is renewable, clean and carbon neutral. Unfortunately, biomass cannot completely take the place of coal for power generation because it is season-dependent and low in calorific density (Thomas et al., 2012). Co-gasification of biomass and coal can be a good solution. With this concept, coal resource can be saved and the biomass resource can be sufficiently explored (Zhang et al., 2016). In the meantime, net carbon discharge for power generation can be readily controlled. In addition, it was reported that synergistic effect could be detected during the co-gasification of some coal and biomass (Pinto et al., 2014). What is more, gasification itself is more effective than the strongly irreversible combustion process (Yan et al., 2013).

Recently, with the advent of fear about climate change, attentions have been focused on the carbon capture and sequestration (CCS) during the thermal conversion of coal. Gasification for hydrogen generation represents the CO_2 pre-combustion capture technology (Babu et al., 2013). This technology is strongly restricted by the gasification equilibrium state. Oxy-fuel combustion represents the in situ capturing technology (Tran et al., 2016). This technology, however, needs the air separation unit which is power-intensive. The post-combustion capturing technologies, like the pressure swing absorption (PSA) (Gasas et al., 2013) and the monoethanolamine (MEA) CO_2 absorption (Reynolds et al., 2015), all have their inherent deficiencies. Recently, the chemical looping process (CLP) has been proposed as one novel method for CO_2 separation. The chemical looping combustion (CLC) and the chemical

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Nomenclature

Parameters

A_{ad}	ash content of air-dried basis
A_d	ash content of dry basis
C_{ar}	carbon content of as received basis
C_{daf}	carbon content of dry-ash-free basis
$C_{exhaust}$	the amount of carbon released [kg/h]
C_{input}	the total amount of carbon brought by feed stock [kg/h]
Cl_{ar}	chlorine content of as received basis
$C_{p,gas}$	specific heat [kJ/(kg K)]
en	specific molar energy [kJ/kg]
ex	total specific exergy [kJ/kg]
ex^{ch}	chemical exergy [kJ/kg]
ex_i^{ch}	standard chemical exergy of species i
ex^{ph}	physical exergy [kJ/kg]
$\sum E_i$	electric power consumed by the pumps and compressors [kW]
En_{in}	energy of the inlet streams [kJ/kg]
En_l	energy loss [kJ/kg]
En_{out}	energy of the outlet streams [kJ/kg]
Ex_{in}	exergy of the inlet streams [kJ/kg]
Ex_l	exergy loss [kJ/kg]
Ex_{out}	exergy of the outlet streams [kJ/kg]
FC_{ad}	fixed carbon content of air-dried basis
FC_d	fixed carbon content of dry basis
h	specific enthalpy [kJ/kg]
H_{ar}	hydrogen content of as received basis
H_{daf}	carbon content of dry-ash-free basis
LHV_{gas}	lower heating value of gas [kJ/kg]
LHV_{solid}	lower heating value of a solid fuel [kJ/kg]
m_{bio}	mass flows of biomass [kg/h]
m_{coal}	mass flows of coal [kg/h]
M_{ad}	moisture content of air-dried basis
M_{ar}	moisture content of as received basis
M_i	mole flow rate of species i [kmol/h]
N_{ar}	nitrogen content of as received basis
N_{daf}	carbon content of dry-ash-free basis
O_{ar}	oxygen content of as received basis
O_{daf}	carbon content of dry-ash-free basis
p_0	environment temperature [Pa]
PSOFC	output electric power from SOFC [120 kW]
P_{turb}	electric power generated by the steam turbine [kW]
R_b	biomass mass fraction
R_{if}	iron to fuel mole ratio
R_{sc}	steam to carbon mole ratio
s	specific entropies [kJ/(kg K)]
s_0	reference specific entropies [kJ/(kg K)]
S_{ar}	sulphur content of as received basis
S_{daf}	carbon content of dry-ash-free basis
T_0	environment temperature [°C]
T_g	gasification temperature [°C]
T_{gas}	actual gas temperature [°C]
V_{ad}	volatile content of air-dried basis
V_d	volatile content of dry basis
w	the mass fraction of moisture
W_u	output work of a unit
Y_i	mass fraction of element i in coal

Greek symbols

η_{cc}	carbon capture rate
η_e	energy efficiency
η_{ex}	exergy efficiency
η_{te}	total energy efficiency
η_{tex}	total exergy efficiency
φ_{dry}	coefficient correlated with the solid fuel composition
χ_i	molar fraction of species i

Abbreviations

ASU	air separation unit
CB-CLP	coal and biomass based chemical looping power generation
CCS	carbon capture and sequestration
CLC	chemical looping combustion
CLH	chemical looping hydrogen
CLOU	chemical looping with oxygen uncoupling
CLP	chemical looping process
CLR	chemical looping reforming
EnBC	energy balance calculation
ExBC	exergy balance calculation
GT	gas turbine
MEA	monoethanolamine
SOFC	solid oxide fuel cell

looping with oxygen uncoupling (CLOU) technologies can be good substitutions for the oxy-fuel combustion since the CLC and CLOU are less power-intensive to generate pure oxygen (Huang et al., 2013; Alexander et al., 2011). The chemical looping hydrogen (CLH) generation and the chemical looping reforming (CLR) (Tao et al., 2015) are also prospective means to get hydrogen with CO_2 capture. CLH can generate pure hydrogen and its CO_2 capture ability is brilliant with proper oxygen carriers. Research has found that most Fe-based oxygen carriers demonstrate higher melting point, better mechanical strength, lower environmental impact and lower cost than the others (Huang et al., 2013). Thus, CLH with Fe-based oxygen carrier is chosen to capture CO_2 in this work. Since the steam gasification process is endothermic, the heat needed can be supplied by the CLOU process with the Cu-based oxygen carrier. In combination with CLH and CLOU, the mineral sequestration which is not power-intensive (Li et al., 2011) is chosen and CO_2 can be permanently stored by forsterite ($2MgO{\cdot}SiO_2$) or serpentine ($3MgO{\cdot}SiO_2{\cdot}2H_2O$) which are naturally common.

In terms of power generation, fuel cell is very promising (Doherty et al., 2010) and the solid oxide fuel cell (SOFC) is chosen to convert the chemical energy of hydrogen into power in this work, and the steam turbine is chosen as the heat recovery unit. With the other aforementioned technologies, a coal and biomass based chemical looping power generation (CB-CLP) system is developed. The schematic diagram of the CB-CLP system is shown in Fig. 1. Biomass and coal are co-gasified with steam in the gasifier and the generated syngas enters the reducer to reduce Fe_2O_3. FeO generated in the reducer then enters the oxidizer to split water. Fe_3O_4 generated in the oxidizer then enters the combustor to regenerate Fe_2O_3. H_2 generated in the oxidizer then enters the SOFC to generate electric power. Sensible heat generated in the system is recycled and generates power with the steam turbine. CO_2 rich depleted syngas from the reducer then enters the sequestration unit.

Besides the CB-CLP system developed in this work, many other similar systems have also been put forward by researchers. Chen once developed a power generation system which integrates the coal gasification, the SOFC and the CLC technologies (Chen et al., 2015). The system is very novel and promising. It used O_2 and CO_2 as the gasification agent and O_2 was obtained by an air separation unit (ASU). Torsten (Methling et al., 2014) recently developed a clean power generation system which combined the biomass fermentation and gasification. The SOFC and the gas