Bioresource Technology 254 (2018) 97–106

Contents lists available at ScienceDirect

Bioresource Technology

journal homepage: www.elsevier.com/locate/biortech

Characterization of a dual fluidized bed gasifier with blended biomass/coal as feedstock

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ARTICLE INFO

Keywords:
Co-gasification
Alkali metals
Synergistic effect
Dual fluidized bed gasifier
Aspen Plus

ABSTRACT

A one-dimensional model is built based on the commercial Aspen Plus software to kinetically simulate the biomass/coal co-gasification process in a dual fluidized bed gasifier. The synergistic effect on the co-gasification kinetics is allowed for, and is coupled with the gas–solid flow hydrodynamics. With the developed model, the effects of different key operating parameters including the biomass blending ratio (R_b), the initial bed temperature (T_g), the feedstock mass flow rate (F_{fs}), the bed material flux (F_{bm}) and the steam to carbon ratio (R_{sc}) on the resultant syngas composition and the supplemental fuel mass flow rate (F_{sf}) are investigated, and the operation parameters are optimized. It is found that increasing R_b and T_g can enhance the gasification, while increasing F_{fs} and R_{sc} restricts the gasification. Increasing F_{bm} has slight effect on the gasification results but can reduce F_{sf}. The cold gas efficiency is up to 78.9% under the proposed optimum condition.

1. Introduction

Biomass currently provides most of the renewable energy (excluding hydroelectricity) consumed in the industrial sector and will continue to do so in the future. It is also the fourth largest fuel source in the world, and shares about 2.7% of the global energy demands (World energy outlook, 2016). Moreover, it is clean and carbon neutral during the thermal conversion. Despite of all these advantages, there are also some inherent disadvantages in terms of biomass utilization. First, the heating value of biomass is low, making its transportation or storage uneconomical. Second, the supply of biomass is seasonally dependent, making it incompetent for large scale utilization. Third, gasification of biomass is apt to generate tar and cause secondary pollution. Compared to biomass, coal is the most abundant but dirtiest fuel in the world. Direct combustion of coal discharges large amount of pollutants and CO_2, which is adverse to the living environment. Although the gasification technology offers a compelling route for clean coal utilization, the relatively low activity of coal char brings about another issue. Moreover, as the non-renewable resource, coal will be exhausted one day in the future.

Co-gasification of biomass and coal is prospective to solve all the above issues. First, the coal consumption per unit power generation can be lowered when biomass is added to the feedstock (Yan et al., 2016a). Second, discharge of pollutants and CO_2 per unit power generation can be reduced (Yan & He, 2017). Third, the co-gasfication temperature is relatively higher, beneficial to the tar decomposition (Xiang et al., 2017). Fourth, the synergistic effect may happen and promotes the char conversion (Yan et al., 2018). Since most of the gasification processes are endothermic, part of the feedstock is burnt to meet the required heat consumption in industry. If pure oxygen is chosen as oxidant, great efficiency penalty will be imposed. If air is chosen as oxidant, the gasification products can be greatly diluted by large amount of N_2. This contradiction can be perfectly solved by the dual fluidized bed (DFB) gasification technology (Yan et al., 2016b), in which the gasification and combustion processes are well separated from each other to avoid the dilution of syngas, and the heat required by the endothermic gasification is transported from the combustor by the circulating bed material like silica sand.

Co-gasification of biomass/coal in the DFB gasifiers draws upon the inherent advantages of both the co-gasification technology and the dual bed gasification technology, making it very promising for the clean and efficient utilization of the biomass and coal resources. Till now, many concerns have been attracted to this topic and many contributions have been done by researchers worldwide. Chen et al. (2017) simulated the biomass/coal co-gasification in an internally circulating fluidized bed (ICFB) gasifier using the kinetic theory of granular mixture. The variations of granular temperatures of the coal and biomass particles against the solid volume fraction, gasification temperature and carbon concentration were particularly investigated. The synergistic effect on the co-gasification kinetics was, however, not considered. Wang and Chen (2013) experimentally investigated the effect of temperature on the composition and lower heating value (LHV) of the syngas from an

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https://doi.org/10.1016/j.biortech.2018.01.067
Received 9 November 2017; Received in revised form 13 January 2018; Accepted 15 January 2018

Nomenclature

a	decay constant
A_b	bubble phase cross-sectional area, [m^2]
A_d	ash content in dried basis, [−]
A_i	pre-exponential factor [1/s]
Ar	Archimedes number
A_t	bed cross-sectional area, [m^2]
C_b	concentration in bubble, [mole/m^3]
C_e	concentration in emulsion, [mole/m^3]
C_j	concentration of species j, [kmole/m^3]
$C_{p,p}$	particle specific heat, [J/(kg·k)]
d_p	particle diameter, [m]
D_B	bubble diameter, [m]
D_{B0}	initial bubble diameter, [m]
D_{BM}	maximum bubble diameter, [m]
D_j	diffusion coefficient, [m^2/s]
D_t	column diameter, [m]
E_i	activation energy [kJ/mol/K]
F_b	molar flow rate in bubble, [mole/s]
F_{bm}	circulating flux in combustor [kg/m^2/h]
F_e	molar flow rate in emulsion, [mole/s]
F_f	feedstock mass flow rate [kg/h]
g	acceleration of gravity, [m/s^2]
h_{be}	bubble-to-emulsion heat transfer coefficient, [W/(m^2·K)]
h_{gp}	gas-to-particle heat transfer coefficient, [W/m^2/K]
H	total enthalpy flow, [kJ/s]
ΔH	enthalpy generation, [J/mole]
k	reaction rate constant
k_g	gas thermal conductivity, [W/(m·K)]
k_s	solid thermal conductivity, [W/(m·K)]
K_{be}	bubble-to-emulsion mass transfer coefficient, [1/s]
L_d	dense bed height, [m]
L_f	freeboard height, [m]
M_{ad}	moisture in air-dried basis, [−]
M_s	mass of bed material, [kg]
$M_{s,i}$	mass of solids in i_{th} stage, [kg]
n	total number of species, [−]
n_d	number of orifices in distributor, [−]
p	operation pressure, [Pa]
P_j	partial pressure of species j, [bar/atm]
Pr_p	Prandtl number, [−]
$r_{(i),j}$	consumption rate of species j in stage i, [kmole/(m^3·s)]
r_{blend}	net increment of r_{coal} [1/s]
r_{coal}	conversion rates of coal char [1/s]
r_{mix}	conversion rates of blended char [1/s]
R_b	biomass blending ratio
R_c	char conversion
Re_p	Reynolds number, [−]
R_g	gas constant, 8.3145, [J/K]
R_{H2O}	steam conversion, [−]
R_{sc}	steam-to-carbon ratio, [−]
S_{cf}	sand circulation flux, [kg/(m^2·s)]
T_b	temperature in bubble, [K]
T_e	temperature in emulsion, [K]
T_g	initial gasification temperature [°C]
U_0	superficial velocity, [m/s]
U_{br}	bubble rise velocity, [m/s]
U_{mb}	minimum bubbling velocity, [m/s]
U_{mf}	minimum fluidization velocity, [m/s]
V_{ad}	volatile in air-dried basis, [−]
V_b	volume of bubble phase, [m^3]
V_e	volume of emulsion phase, [m^3]
x	conversion [%]
Y_{biom}	yield from biomass [%]
Y_{coal}	yield from coal [%]
Y_{tv}	volatile fraction by calculation [%]
Y_v	volatile fraction by proximate analysis [%]
z	length of PFR, [m]
z_f	height above distributor, [m]

Greek symbols

δ_b	bubble phase volume fraction, [−]
ε_b	bubble phase voidage, [−]
ε_{mf}	emulsion voidage at minimum fluidization, 0.4, [−]
μ_g	gas viscosity, [kg/(m·s)]
ρ_g	gas density, [kg/m^3]
ρ_p	particle density, [kg/m^3]
τ	residence time of particle in bubble, [s]
ϕ_d	dense phase solids volume fraction, [−]
$\phi*$	saturation carrying capacity, [−]
ϕ_f	freeboard solids volume fraction, [−]
ψ_{char}	one minus char conversion, [−]
Ψ_i	structure parameter

Abbreviations

AAEM	alkali and alkaline metal
BAM	bubble assemblage model
BFB	bubbling fluidized bed
CFB	circulating fluidized bed
CSTR	continuous stirred tank reactor
DFB	dual fluidized bed
LHV	lower heating value
PFR	plug flow reactor
WGS	water–gas shift
ICFB	internally circulating fluidized bed

autothermal fluidized bed gasifier, and found that higher reaction temperature leaded to higher H_2 and CO contents, as well as higher energy and exergy efficiencies. But, the syngas LHV decreased with the temperature increment. Saw and Pang (Saw & Pang, 2013) studied the influence of the lignite blending ratio on the producer gas composition and tar content in a 100 kW DFB steam gasifier, and found that increasing the lignite blending ratio could increase the H_2/CO ratio and reduce the tar concentration. In addition, the synergistic effect was detected in the research. Aigner et al. (2011) studied the co-gasification of coal and wood in a 100 kW DFB gasifier, and found that the producer gas composition varied linearly with linear variation of the wood blending ratio. The contents of NH_3 and H_2S in the producer gas fell with decreasing coal blending ratio. Masnadi et al. (2015) investigated the synergistic effects during the steam co-gasification of switchgrass and coal in a pilot-scale bubbling fluidized bed gasifier, and found that the hydrogen concentration, the cold gas efficiency, the gas yield and the higher heating value (HHV) of the producer gas were enhanced remarkably relative to single-fuel gasification with the switchgrass added to coal. The alkali metals in biomass ash synergized with coal and catalyzed the gasification. Miccio et al. (2012) experimentally studied the co-gasification of biomass and brown coal in an ICFB gasifier, and found that the hydrogen concentration in the producer gas was up to 35% in the best case. The tar content was reduced greatly when changing from inert to partially catalytic bed.

From the literature review, it is known that research on the biomass/coal co-gasification in the DFB gasifiers is mainly restricted to the experimental level. Kinetic simulations of the co-gasification process in DFB, especially those considering the synergistic effect, are rarely