Energy Conversion and Management 127 (2016) 612–622

Contents lists available at ScienceDirect

Energy Conversion and Management

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

One-dimensional modeling of a dual fluidized bed for biomass steam gasification

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ARTICLE INFO

Article history:
Received 6 May 2016
Received in revised form 6 September 2016
Accepted 7 September 2016

Keywords:
Dual fluidized bed (DFB)
Bubbling fluidized bed (BFB)
Steam gasification
Simulation
Biomass

ABSTRACT

A one-dimensional model for biomass steam gasification in dual fluidized bed gasifiers is set up with the assistance of Aspen Plus. Both the hydrodynamic and kinetic processes are coupled and simulated. The model predictions agree well with the experimental data reported in the literature. Sensitivity analyses are also performed to investigate the effects of different operating parameters, including the inlet biomass flow rate (F_{bio}), the steam-to-biomass ratio (R_{sb}), the sand circulation flux (S_{cf}) and the flow rate of the additional methane burnt in the riser (F_m). Under the benchmark conditions, the mole fractions of H_2 and CO_2 increase along the height of the bubbling fluidized bed (BFB), while those of CO and CH_4 decrease. The gasification temperature decreases slightly against the height in the bed zone, but increases in the freeboard zone. The superficial velocity slightly increases and the bubbles grow against the height in the BFB. Increasing both F_{bio} and R_{sb} restricts the gasification process, increasing S_{cf} only slightly affects the gasification results, and increasing F_m promotes the gasification process.

1. Introduction

Biomass is one of the most promising renewable fuels in the world due to its abundance and wide distribution. It is much cleaner and less carbon-intensive than coal and can displace some fossil fuels for power generation. However, its calorific value is relatively low, and the storage and transportation of biomass are costly, which makes it uneconomical to use biomass directly. One efficient way to resolve these issues is the biomass gasification technology [1]. For this technology, the gasifier is usually a fixed, or fluidized bed, while the main gasification agents are usually air and steam. Since biomass steam gasification is mostly endothermic, additional heat is required and usually obtained by burning residual char and some additional fuels. For conventional fixed or fluidized bed gasifiers, biomass is partially oxidized by air to supply the heat required by the gasification process. This type of gasification process is simple, but the resulting syngas calorific value is relatively low since the combustible species can be greatly diluted by large amounts of nitrogen. The dual fluidized bed (DFB) gasifiers solve this issue by having one fluidized bed serve as a gasification reactor and the other as a combustion reactor, with the combustion and gasification processes separated. Each DFB has one or several cyclones to prevent the combustor flue gas from mixing with the syngas, while the bed particulate material circulates between the two reactors as the heat transfer medium. Usually, a fast fluidized bed is chosen as the combustor so that the bed material can be transported, whereas a bubbling fluidized bed (BFB) serves as the gasifier to provide sufficient residence time for the biomass particles.

The DFB has its advantages, but its operation is hard to control due to the pressure balance and the heat balance between the two beds. To assist with understanding the characteristics of the DFB, simulation is helpful. A number of different simulation methods and models have been proposed till now, including the zero-dimensional, the one-dimensional, the two-dimensional and the three-dimensional models. In terms of the chemical reactions, there are equilibrium models, non-equilibrium models and kinetic models. With respect to coupling, there are models which couple hydrodynamics and chemical reactions, and models which only consider the reactions.

Li et al. [2] set up a zero-dimensional equilibrium model using the non-stoichiometric method for biomass gasification in fluidized beds. This model also considered non-equilibrium factors and gave good agreement with experimental results. Hejazi et al. [3] developed an equilibrium model for steam gasification of biomass with CO_2 captured by limestone using the stoichiometric equilibrium model. Effects of different operation parameters on

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http://dx.doi.org/10.1016/j.enconman.2016.09.027
0196-8904/

Nomenclature

a	decay constant
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]
F_b	molar flow rate in bubble [mole/s]
F_{bio}	biomass mass flow rate [kg/h]
F_e	molar flow rate in emulsion [mole/s]
F_m	methane 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_{bd}	bubble-to-dense phase mass transfer coefficient [1/s]
L_d	dense bed height [m]
L_f	freeboard height [m]
m_{char}	char mass flow rate [kg/s]
M_{char}	molecular weight of char [kg/kmole]
M_{ar}	moisture in as-received 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]
Pr_p	Prandtl number [–]
BFB	bubbling fluidized bed
CFD	computational fluid dynamics
CSTR	continuous stirred tank reactor
D	dense phase
DFB	dual fluidized bed
Ad	ash content in dried basis [–]
Ab	bubble phase cross-sectional area [m^2]
Ar	Archimedes number
r(i),j	consumption rate of species j in stage i [kmole/(m^3·s)]
Rep	Reynolds number [–]
Rg	gas constant, 8.3145 [J/K]
RH2O	steam conversion [–]
Rsb	steam-to-biomass ratio [–]
Scf	sand circulation flux [kg/(m^2·s)]
Tb	temperature in bubble [K]
Te	temperature in emulsion [K]
U0	superficial velocity [m/s]
Ubr	bubble rise velocity [m/s]
Umb	minimum bubbling velocity [m/s]
Umf	minimum fluidization velocity [m/s]
Vd	volatile in dry basis [–]
Vb	volume of bubble phase [m^3]
Ve	volume of emulsion phase [m^3]
Yj	mass fraction of species j
z	length of PFR [m]
zf	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 [–]
η_{char}	char mass fraction [–]
μ_g	gas viscosity [kg/(m·s)]
θ_i^C	calculated volume fraction of species i [–]
θ_i^E	experimental volume fraction of species i [–]
ρ_g	gas density [kg/m^3]
ρ_p	particle density [kg/m^3]
ς	root-mean square sum of error [–]
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 [–]

Abbreviations

B	bed
FB	freeboard
FICFB	fast internally circulating fluidized bed
LHV	low heating value
PFR	plug flow reactor
WGS	water-gas shift

the gasification results were revealed with in situ CO_2 capture. However, an equilibrium model is not a good choice for modeling a gasification process since the rates of the gasification reactions, especially the heterogeneous ones, are relatively slow. Zhu et al. [4] developed a kinetic model for biomass gasification in a DFB using Aspen Plus, without coupling the hydrodynamics. Their simulation results were compared with experimental data, and sensitivity analyses were conducted. Practically, the hydrodynamics can greatly affect the gasification reactions by affecting the interphase heat and mass transfer and determining the gasification residence time in a given reactor. Kaushal et al. [5] developed a one-dimensional modeling tool for an 8 MW_{th} DFB which coupled the hydrodynamic and kinetic processes. Their model considered two phases, bubble and emulsion phases, and the simulation predictions were compared with experimental data. In their model, the interphase heat transfer and the tar decomposition process were not considered. Nikoo [6] developed a one-dimensional model for biomass gasification in a bubbling bed reactor based on Aspen Plus. This model considered the bed and the freeboard zones as a series of continuously stirred tank reactors (CSTRs) and coupled the hydrodynamic calculations with the reaction kinetics. Since there are bubbles appearing in the dense bed, it could be oversimplified to treat the bed zone as CSTRs. Liu [7] implemented a three-dimensional full-loop numerical simulation for biomass gasification in a DFB with the commercial Barracuda software. The simulation results were tested against experimental data, and the effects of particle size distribution and drag models were investigated. The three-dimensional numerical simulation of the DFB is definitely promising, but it is very time-consuming and needs powerful computer resources.

Since the zero-dimensional equilibrium models tend to over-simplify the problem, and the three-dimensional computational