Applied Energy 209 (2018) 43–55

Contents lists available at ScienceDirect

Applied Energy

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

Biomass gasification for syngas and biochar co-production: Energy application and economic evaluation

Zhiyi Yao[a,b], Siming You[b], Tianshu Ge[c], Chi-Hwa Wang[a,b,*]

[a] *Department of Chemical and Biomolecular Engineering, National University of Singapore, 4 Engineering Drive 4, 117585, Singapore*
[b] *NUS Environmental Research Institute, National University of Singapore, 1 Create Way, Create Tower #15-02, 138602, Singapore*
[c] *School of Mechanical Engineering, Shanghai Jiaotong University, Shanghai 200240, China*

HIGHLIGHTS

- A gasification model was developed to predict the production of syngas and biochar.
- Economic value of syngas and biochar production was evaluated based on the model.
- The heat and mass transfer in the reactor was modelled by a three-region approach.
- The effects of various factors on syngas and biochar production were studied.

ARTICLE INFO

Keywords:
Biochar
Biomass gasification
Energy efficiency
Economics, syngas

ABSTRACT

Syngas and biochar are two main products from biomass gasification. To facilitate the optimization of the energy efficiency and economic viability of gasification systems, a comprehensive fixed-bed gasification model has been developed to predict the product rate and quality of both biochar and syngas. A coupled transient representative particle and fix-bed model was developed to describe the entire fixed-bed in the flow direction of primary air. A three-region approach has been incorporated into the model, which divided the reactor into three regions in terms of different fluid velocity profiles, i.e. natural convection region, mixed convection region, and forced convection region, respectively. The model could provide accurate predictions against experimental data with a deviation generally smaller than 10%. The model is applicable for efficient analysis of fixed-bed biomass gasification under variable operating conditions, such as equivalence ratio, moisture content of feedstock, and air inlet location. The optimal equivalence ratio was found to be 0.25 for maximizing the economic benefits of the gasification process.

1. Introduction

The shortage of fossil fuel reserves and global warming sparked an eruption of research and development for renewable energy [1]. Among the plethora of renewable energy sources and technologies, thermochemical conversion of biomass is regarded to be one of feasible routes to realize a sustainable future since biomass is a carbon neutral energy source and can reduce our dependence on fossil fuels [2]. Downdraft gasification has been proved as a standout choice for small to medium size throughputs [3,4] due to its higher efficiency as compared to other thermochemical processes such as pyrolysis, direct combustion and liquefaction [5–7].

Recently, significant attention has been paid to the numerical modelling of the gasification process which plays an important role in understanding the various physiochemical aspects of interaction within the reactor of gasification. In addition, the model could be used as a cost effective tool to predict and optimize the energy performance of gasification systems. The theoretical characterization of the four different zones in a fixed-bed gasifier and relevant reactions have been explored extensively since the early 1930s [6]. Di Blasi first proposed a complex network of reaction equations that were classified into four different gasification stages: (i) drying, (ii) pyrolysis, (iii) combustion, and (iv) reduction, with outputs being time-based axial gas composition and temperature profiles [8]. Later on, several researchers developed similar models to predict syngas composition, considering either single one stage (only reduction zone) or multi-stages of the process [9–12]. These models vary in several aspects, such as reactor configurations and reaction kinetics [13].

---

[*] Corresponding author at: Department of Chemical and Biomolecular Engineering, National University of Singapore, 4 Engineering Drive 4, 117585, Singapore.
E-mail address: chewch@nus.edu.sg (C.-H. Wang).

http://dx.doi.org/10.1016/j.apenergy.2017.10.077
Received 10 July 2017; Received in revised form 6 October 2017; Accepted 23 October 2017

Nomenclature

A	cross sectional area of the bed [m^2]
A_v	specific surface area [m^{-1}]
c_p	specific heat capacity [$J\,kg^{-1}\,K^{-1}$]
D	diffusivity [$m^2\,s^{-1}$]
d	diameter [m]
F	mass flow rate [$kg\,s^{-1}$]
f_1	first frictional factor [$kg\,m^{-3}\,s^{-1}$]
f_2	second frictional factor [$kg\,m^{-4}$]
G	gas mass flux [$kg\,m^{-2}\,s^{-1}$]
ΔH	enthalpy change [$J\,mol^{-1}$]
h	heat transfer coefficient [$W\,m^{-2}\,K^{-1}$]
k	mass transfer coefficient [$m\,s^{-1}$]
L	reactor length in axial direction [m]
L*	characteristic length [m]
M	molecular weight [$kg\,mol^{-1}$]
Nu	Nusselt number [–]
q	heat flux [$W\,m^{-2}$]
R	reaction rate [$mol\,m^{-3}\,s^{-1}$]
RM	removing rate [$kg\,s^{-1}$]
Re	Reynolds number [–]
r_{vol}	volume reaction rate [$mol\,m^{-3}\,s^{-1}$]
r_{suf}	surface reaction rate [$mol\,m^{-2}\,s^{-1}$]
Sc	Schmidt number [–]
Sh	Sherwood number [–]
s_k	film diffusion rate [$kg\,m^{-2}\,s^{-1}$]
T	temperature [K]
t	time [s]
u	velocity [$m\,s^{-1}$]
Y	mass fraction [–]

Greek letters

ε	porosity [–]
ρ	density [$kg\,m^{-3}$]
υ	stoichiometric number [–]
μ	effective viscosity [$kg\,m^{-1}\,s^{-1}$]
β	fluid coefficient of thermal expansion [K^{-1}]
η	dynamic viscosity [$Pa\,s^{-1}$]
$\in_t$	turbulent dissipation rate [$m^2\,s^{-3}$]
$\in$	particle emissivity [–]
σ	Stefan–Boltzmann constant [$W\,m^{-2}\,K^{-4}$]
κ	thermal conductivity [$W\,m^{-1}\,K^{-1}$]

Subscripts

a	the region above air inlet location
b	fixed bed
des	desorption
f	forced convection region
g	pertains to gas phase
gs	heat or mass transfer between gas phase and solid phase
in	air inlet
i	pertains to specie or component in gas phase with index i
j	pertains to specie or component in solid phase with index j
k	pertains to reaction number with index k
m	mixed convection
n	natural convection
s	pertains to solid phase
sat	saturation
ss	heat or mass transfer in solid phase
suf	pertains to surface reactions
tm	turbulent mixing
vap	vaporization
vol	volume to volume reactions
w	water

However, most existing models focus only on the prediction of temperature profile and syngas composition without considering biochar production [7,11,14–16]. Besides syngas, biochar is another valuable product from the gasification process due to its potential ability of improving soil quality and sequestering carbon [17–19]. To predict biochar production, the heat and mass transfer on a particle level needs to be considered. Some models do consider the particle-level heat and mass transfer but they treat both solid phase and gas phase as continuous phases (which is also referred as Euler–Euler approach). This approach is appropriate only if the influential parameters (e.g., particle size, and temperature and species concentration gradient inside the particle) of a single particle on gasification performance are negligible [20]. However, it has been suggested that considering the single particle parameters and-intra-particle phenomenon can significantly improve the accuracy of gasification models in predicting important design parameters of reactor [8,21]. In this case, biomass gasification modelling should be considered as a multi-scale problem [22]; that is, the molecular level, single particle level and reactor level should all be considered. One method to solve the multi-scale problem is the Discrete Phase Model (DPM). This modelling approach treats the gas phase as quasi-continuous while each particle is tracked in a Lagrange approach. The governing equations of each particle are solved simultaneously with gas-phase balances in each time step. Several works have applied this approach to simulate the thermochemical conversion of biomass [23–25]. However, this approach is only suitable for lab-scale gasifiers with a limited number of particles due to the high computational power required [20]. An alternative method to solve solid phase with reasonable computational time is Representative Particle Model (RPM). In each cell, balance equations are solved for one representative particle and all the particles in the same cell are assumed to have the same characteristics. There are mainly two types of single particle models which could be easily coupled with the fluid phase: shrinking sphere model and shrinking core model [26,27]. In the shrinking sphere model, the size of biomass particles reduces while their density remaining constant. The particle is assumed to be impervious with all the reaction details lumped at the gas-solid interface. As for the shrinking core model, both the size and density of biomass particles vary. Wurzenberger coupled RPM with entire fixed-bed fluid model to simulate pyrolysis and combustion processes [28,29]. In his work, the reactor was discretized in the axial direction and the particle domain were discretized in the radial direction so the model was also described as 1D + 1D. Later on several research works have been conducted on multi-scale modelling of combustion and pyrolysis reactors using coupled 1D + 1D model [20,30].

In addition, there is a difference in the velocity profile between the region above air inlet and the region below air inlet. Inlet air mainly flows towards the bottom of the reactor and within this region, heat and mass transfer is dominated by forced convection. In the region above the air inlet, hot air tends to go up and the heat and mass transfer within this region is mainly controlled by natural convection. In the region near the air inlet, hot air tends to go up but pressure gradient forces the air to flow towards the bottom. These two driving forces are in the opposite direction and this special case is called mixed convection [31]. A number of studies have been conducted to investigate natural convection, forced convection and mixed convection in fixed-bed [31–34]. However, to the best of our knowledge, the application of