Applied Energy xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Applied Energy

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

Gasification behavior of coal and woody biomass: Validation and parametrical study

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HIGHLIGHTS

- Numerical modeling and experimental diagnostics of entrained flow gasification.
- Obtain the effect of gasification of Kentucky coal and wood waste.
- Obtain the effect of equivalence ratio, pressure and temperature.
- Kentucky coal produced higher gasification efficiency as compared to wood.
- The gasification efficiency most sensitive to equivalence ratio.

ARTICLE INFO

Article history:
Received 1 June 2015
Received in revised form 13 May 2016
Accepted 20 May 2016
Available online xxxx

Keywords:
Entrained flow gasification
Kentucky coal
Woody Biomass
Gasification efficiency
Numerical modeling
Lagrangian–Eulerian

ABSTRACT

The entrained flow gasification of two feedstocks (Kentucky coal and woody biomass) have been investigated in this study both numerically and experimentally. Previously, there had been no study that investigated the centerline parameters during the experimental gasification of Kentucky coal and biomass utilizing drop tube reactor (DTR). These high quality centerline experiments provide enough data for high fidelity model development and used for an innovative gasifier design. This work investigates the gasification behavior of Kentucky coal and wood waste under different gasification parameters including equivalence ratio, pressure and temperature. The experimental study was conducted in the air-blown atmospheric DTR experimental facility at the Waste-2-Energy Laboratory at Masdar Institute. The measured centerline temperature, exit gas composition, and SEM images was obtained for model validation and to gain better insight into the gasification of the two different feedstock particles. The Lagrangian–Eulerian based numerical model predicted the experimental results reasonably. The effect of the fuel type on the gas composition along the centerline of the gasifier indicated that Kentucky coal attained higher gasification efficiency when compared to that of wood waste. Moreover, the gasification efficiency was most sensitive to the equivalence ratio.

1. Introduction

The potential for gasification to be employed in carbon capture through the utilization of integrated gasification combined cycle (IGCC), the flexibility to accommodate multiple feedstocks and their ability to be used for cogeneration are the chief reasons for regaining popularity of entrained flow gasifiers (EFG) [1]. Given this flexibility, EFGs can be deployed to convert the worldwide biomass potential to utilizable syngas. The total sustainable worldwide biomass energy potential is about 100 EJ/a (the share of woody biomass is 41.6 EJ/a), which is currently about 30% of the total global energy consumption [2]. A comparison between the available potential and with current use shows that less than two-fifths of the existing biomass potential is used, indicating an opportunity for gasification almost in every country [2].

As full scale gasification experiments are costly and at a limited temperature and species distribution data, numerous systematic and high fidelity modeling investigations were reported for coal, and less for biomass feedstock [3–13]. These studies are at different modeling complexity levels, resolution, and computational costs. The assumption of instantaneous equilibrium and equal diffusivity appears in other literature work for numerical solid conversion [14–17] is considered to be too generic to carry accurate parametric studies and different gasification conditions.

Watanabe and Otaka [4] developed a three-dimensional model based on the Lagrangian–Eulerian scheme for a 2-ton per day research scale coal EFG. They predicted exit temperature and

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http://dx.doi.org/10.1016/j.apenergy.2016.05.119
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Nomenclature

Acronyms

1-D	one dimensional
2-D	two dimensional
3-D	three dimensional
APM	Advanced Powder Metallurgy
BYU	Brigham Young University
CFD	Computational Fluid Dynamics
GE	Gas Efficiency
CPD	chemical percolation devolatilization
DAF	Dry Ash Free
DNS	Direct Numerical Simulation
DTR	drop tube reactor
FCC	Fixed Carbon Content
FG-DVC	functional group-depolymerization vaporization cross-linking
FLASH	Five Organic Elemental Analyzer
GC–MS	Gas Chromatography–Mass Spectrometry
HHV	Higher Heating Value
LES	Large Eddy Simulation
LHV	Lower Heating Value
MSW	Municipal Solid Waste
IGCC	integrated gasification combined cycle
PCGC	Pulverized Coal Gasification or Combustion
PPM	Parts Per Million
RANS	Reynolds Averaged Navier–Stokes
SEM	scanning electron microscope
SST	shear stress transport
TGA	Thermogravimetric Analysis

Chemical notations

C	atomic carbon
C_2H_4	ethylene
CH_4	methane
CO	carbon monoxide
CO_2	carbon dioxide
C(s)	solid carbon
H_2	hydrogen
H_2O	steam
H_2S	hydrogen sulfide
N_2	nitrogen
NH_3	ammonia
NO_x	nitrogen oxide
O_2	oxygen
S	atomic sulfur
SO	sulfur monoxide
SO_2	sulfur dioxide

Arabic and Greek notations units

A	frequency factor (varies)
A	surface area (m^2)
A_g	specific char surface area (m^2/g)
C	molar concentration ($kmol/m^3$)
C_D	drag coefficient (–)
c_p	specific heat at constant pressure (J/(kg K))
D	diameter (m)
D_i	diffusion coefficient (m^2/s)
E	total energy (J)
e	energy (J)
E_a	activation energy (J/kmol)
g	gravitational acceleration (m/s^2)
k	thermal conductivity (W/(m K))
k	turbulent kinetic energy (m^2/s^2)
k_i	Intrinsic reaction rate (varies)
L	length (m)
m	mass (kg)
M_w	molecular weight (kg/kmol)
n	reaction order (–)
Nu	Nusselt number (–)
P	power (W)
P	pressure (Pa)
Pr	Prandtl number (–)
Re	Reynolds number (–)
R	reaction rate (varies)
R_u	universal gas constant (J/(kmol K))
S	source term (varies)
Sh	Sherwood number (–)
T	temperature (K)
t	time (s)
u	velocity vector (m/s)
u'	velocity fluctuation (m/s^2)
x	molar fraction (–)
Y	mass fraction (–)
α^*	damping coefficient k–ω SST model (–)
$\alpha_{1,2}$	yield factor devolatilization model (–)
β	temperature exponent (–)
ε	dissipation rate (m^2/s^3)
ε_r	effectiveness factor (–)
η	efficiency (–)
μ	molecular viscosity (Pa s)
v	kinematic fluid viscosity (m^2/s)
ω	specific dissipation rate (1/s)
Φ	equivalence ratio; PDF look-up table; Thiele modulus (–)
ρ	density (kg/m^3)
σ	Stefan–Boltzmann constant ($W/(m^2 K^4)$)
ε	emissivity (–)

gasification species at reasonable accuracy in comparison to the experimental data. Their model however was unfit to use it for biomass. Chen et al. [5] numerically investigated the performance of a two-stage entrained-flow gasifier using Taiheiyo coal. They reported that the choice of reaction modeling had great effect on the temperature and syngas composition, and make it impossible to use them for other feedstock. Janajreh and Alshrah predicted the centerline gasifier temperature of their asymmetrical down draft type biomass gasifier following high fidelity numerical modeling. They used 3 homogeneous and 3 heterogeneous reactions with specific kinetic values. However, no syngas measurement was experimentally reported for modeling validated. Abani and Ghoniem [6] investigated coal gasification in an entrained flow gasifier. Although they gave more attention into turbulence using Large Eddy Simulation (LES) and RANS for the gas phase, the two models were close in their prediction. They, however, highlighted the importance of devolatilization reaction for better matching the experimental results reported by Brown et al. [18]. Ghenai and Janajreh [8] studied numerically the effect of co-firing of biomass (wheat straw) and bituminous Canadian coal. Their mathematical model was based on turbulent flow (RNG k–ε model) and two-mixture fractions for the combustion species. Although they showed NO_x and CO_2 concentration decreased along the centerline with the addition of wheat straw their assumption of instantaneous equilibrium, using the pdf combustion model was restrictive at lower temperature, i.e. partial combustion or gasification. Jeong et al. [9] reported reasonable and comparable results to Wabash plant data after integration an improved char gasification model

Please cite this article in press as: Adeyemi I et al. Gasification behavior of coal and woody biomass: Validation and parametrical study. Appl Energy (2016), http://dx.doi.org/10.1016/j.apenergy.2016.05.119