Fuel 135 (2014) 468–481

Contents lists available at ScienceDirect

Fuel

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

A study on the dynamic combustion behavior of a biomass fuel bed

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HIGHLIGHTS

- We study combustion dynamics of a fuel bed in a BioGrate boiler with a model.
- Pyrolysis rate equations are defined for the debarking material used as fuel.
- The reaction rate are incorporated into the model and it is used to study dynamics.
- The dynamics are studied by inducing changes into the primary airflow.
- The combustion dynamics are rapid and dependent on fuel composition.

ARTICLE INFO

Article history:
Received 1 April 2014
Received in revised form 3 July 2014
Accepted 8 July 2014
Available online 19 July 2014

Keywords:
Biomass
BioGrate boiler
Combustion dynamics
Pyrolysis
Reaction rates

ABSTRACT

The main objective of this research was to study fuel bed combustion dynamics of a BioGrate boiler with a mechanistic model. First, the fuel specific pyrolysis reaction rates were experimentally determined for the model. Second, the model was validated and finally, it was used to investigate the effects of the primary air flows on drying, pyrolysis and char consumption rates occurring inside the fuel bed. The research results are presented and the role of the dynamic behavior of the reactions on the biomass combustion process discussed.

1. Introduction

Due to increasing environmental concerns related to energy production, biomass is receiving increasing attention as an alternative energy resource to fossil fuels. However, biomass is associated with varying fuel composition; in addition, it is highly dependent on storing conditions as well as on local and seasonal factors. These variations significantly affect the efficiency of power production resulting in increased pollution and lowering of the economic potential of this renewable material. As a consequence a fuller understanding of the factors which affect the efficiency of power production is particularly important for the further development of these types of energy systems. Mathematical models have shown to be an excellent tool in assessing the complex physical phenomena of biomass combustion.

Numerous works have addressed combustion behavior through modeling. In addition laboratory experiments have been performed to support these modeling studies. Saastamoinen et al. [1] experimentally investigated the combustion of wood with different moisture contents and with different air flows. The researchers presented correlations which allow the prediction of the combustion front propagation velocity from the physical parameters of fuel and the air flow. Shin and Choi [2] utilized modeling to determine the effect of different parameters on the combustion of municipal waste. The results indicated that a low air flow rate limits the combustion rate, whereas, an excessively high flow rate results in flame extinction. Van der Lans et al. [3] described straw combustion with a two dimensional steady-state model and studied the effect of the combustion parameters on the burning of the fuel bed. Goh et al. [4] have developed a model to simulate an incinerator bed. The modeling and experimental results indicated that grate mixing – which is characterized by “random walk” mixing – can be mathematically modeled with a procedure based on swap probability. Yang et al. [5] developed a 2-D model to

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http://dx.doi.org/10.1016/j.fuel.2014.07.015

Nomenclature

A	pre-exponential factor (s^{-1})
A_{pyr}	pre-exponential factor of a pyrolysis reaction (s^{-1})
C_{CH4}	concentration of methane (mol/cm^3)
C_{CO}	concentration of carbon monoxide (mol/cm^3)
C_{H2}	concentration of hydrogen (mol/cm^3)
C_{H2O}	concentration of steam (mol/cm^3)
C_{O2}	concentration of oxygen (mol/cm^3)
$C_{p,\mathrm{H2O}}$	heat capacity of liquid water (J/(kg K))
C_s	heat capacity of the solid phase (J/(kg K))
d_{cavity}	average cavity diameter (m)
$D_{g,i}$	gas-phase diffusivity of component i (m^2/s)
d_p	particle diameter (m)
E	activation energy (J/mol)
H_g	enthalpy of the gas phase (J/kg)
H_{vap}	heat of vaporization of water (J/kg)
I^-	energy flux in a negative direction (W/m^2)
I^+	energy flux in a positive direction (W/m^2)
k_a	absorption coefficient (m^{-1})
$k_{c,i}$	mass transfer coefficient for the gaseous component i (kg/(m^3 s))
$k_{eff,i}$	effective reaction constant of a heterogeneous reaction i (kg/(m^3 s))
k_g	heat conductivity of the gas inside the wood pores (W/(m K))
$k_{gasi,\mathrm{CO2}}$	reaction constant of char gasification with carbon dioxide (kg/(m^3 s))
$k_{gasi,\mathrm{H2O}}$	reaction constant of char gasification with water steam (kg/(m^3 s))
k_s	scattering coefficient (m^{-1})
$k_{s,\mathrm{C}}$	rate constant for the char reaction with oxygen (kg/(m^3 s))
$k_{s,\mathrm{CO2}}$	rate constant for the char reaction with carbon dioxide (kg/(m^3 s))
$k_{s,\mathrm{H2O}}$	rate constant for the char reaction with water (kg/(m^3 s))
$k_{s,i}$	reaction rate constant for the component i (kg/(m^3 s))
$m_{1,k}$	estimated mass of the first volatile component at time instance k (mg)
$m_{2,k}$	estimated mass of the second volatile component at time instance k (mg)
m_{meas}	measured mass of a biomass sample (mg)
$Q_{g,i}$	energy produced or consumed by a gas phase reaction i (J/(m^3 s))
$Q_{s,i}$	energy produced or consumed by a solid phase reaction i (J/(m^3 s))
Re	Reynolds number
$r_{g,\mathrm{CH4}}$	oxidation rate of methane (kg/(m^3 s))
$r_{g,\mathrm{CO}}$	oxidation rate of the carbon monoxide (kg/(m^3 s))
$r_{g,\mathrm{H2}}$	oxidation rate of hydrogen (kg/(m^3 s))
$r_{g,i}$	reaction rate of the gaseous component i (kg/(m^3 s))
$r_{s,\mathrm{H2O}}$	drying rate of fuel (kg/(m^3 s))
$r_{s,j}$	rate of reaction of the solid component j (kg/(m^3 s))
$r_{s,pyr}$	reaction rate of pyrolysis (kg/(m^3 s))
S	density number (m^{-1})
Sc	Schmidt number
T	temperature (K)
T_g	temperature of the gas phase (K)
t_k	time instance k (s)
T_s	temperature of the solid phase (K)
v_g	gas flow velocity (m/s)
X	degree of conversion of char
x	vertical coordinate (m)
Y_{C3H8}	mass fraction of a pyrolytic component reacting to C_3H_8
Y_{CH4}	mass fraction of a pyrolytic component reacting to CH_4
Y_{CO}	mass fraction of a pyrolytic component reacting to CO
Y_{CO2}	mass fraction of a pyrolytic component reacting to CO_2
$Y_{g,i}$	mass fraction of the gaseous component i
Y_{H2}	mass fraction of a pyrolytic component reacting to H_2
Y_{H2O}	mass fraction of a pyrolytic component reacting to H_2O
Y_{tar}	mass fraction of a pyrolytic component reacting to tar
i	mass fraction of the first volatile component in a biomass sample
ε_b	bed porosity
$\varepsilon_{particle}$	particle porosity
κ_{conv}	heat convection coefficient between the gas and solid phases (W/(m^2 K))
κ_{fiber}	heat conductivity of wood fiber (W/(m K))
κ_{max}	maximum heat transfer coefficient (W/(m K))
κ_{min}	minimal heat conduction coefficient (W/(m K))
κ_s	heat conduction coefficient of the solid matter (W/(m K))
$\kappa_{s,rad}$	radiative heat transfer coefficient of the solid matter (W/(m K))
$\kappa_{s,eff}$	effective heat conduction coefficient of the solid matter (W/(m K))
ρ_c	mass concentration of char (kg/m^3)
ρ_{CO}	mass concentration of carbon monoxide (kg/m^3)
ρ_g	mass concentration of the gas phase (kg/m^3)
ρ_{H2}	mass concentration of hydrogen (kg/m^3)
ρ_{O2}	mass concentration of oxygen (kg/m^3)
ρ_s	mass concentration of the solid phase (kg/m^3)
$\rho_{s,j}$	mass concentration of the solid component j (kg/m^3)
ρ_v	mass concentration of volatiles (kg/m^3)
ρ_w	mass concentration of water (kg/m^3)
σ	Stefan–Boltzman constant (W/(m^2 K^4))

simulate MSW incineration on a traveling bed and the results showed that the effect of channeling can increase the concentrations of hydrocarbons in flue gas due to poor mixing. Ashtana et al. [6] has developed a static model to describe grate combustion in an MSW boiler. The modeling work revealed the presence of two combustion fronts above which char reduction reactions occur. A study by Kær [7] on the modeling of a straw fired boiler suggested that poor mixing of flue gases and secondary air results in high CO concentrations and in unburnt carbon in fly ash. Zhou et al. [8] investigated the combustion of a straw bed by using a mathematical model. The work suggested that the effective heat conductivity of the bed, the straw heat capacity and the bed packing have the most influence on the quality of the model predictions. A two-dimensional, steady model of straw combustion presented in Miljkovic et al. [9] demonstrated that modeling can provide information like a temperature profile of the fuel bed, a combustion rate and the produced chemical species which would not otherwise be available. Girgis and Hallett [10] used a mathematical model and experiments to analyze combustion in an overfeed packed bed. In that study, the pyrolysis activation energy was adjusted to improve the model fit of the experimental results. Hallett et al. [11] studied the effect of char particle size non-uniformity on combustion and gasification in an overfed reactor both experimentally and with a model. They found that a volume-surface mean diameter can be used to describe non-uniformly sized particles. Combustion in a conical grate boiler was described mathematically by Boriouchkine et al. [12] to provide information on the combustion characteristics of woody biomass, with specific emphasis on the effects of moisture content, particle size and air flow on the combustion in a BioGrate boiler.