ARTICLE IN PRESS

INTERNATIONAL JOURNAL OF HYDROGEN ENERGY XXX (2018) 1–18

Available online at www.sciencedirect.com

ScienceDirect

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

Gas-phase transport and entropy generation during transient combustion of single biomass particle in varying oxygen and nitrogen atmospheres

Linwei Wang, Nader Karimi, Manosh C. Paul*

Systems, Power & Energy Research Division, School of Engineering, University of Glasgow, Glasgow G12 8QQ, United Kingdom

ARTICLE INFO

Article history:
Received 25 November 2017
Received in revised form
8 March 2018
Accepted 9 March 2018
Available online xxx

Keywords:
Biomass
Entropy generation
Single particle combustion
Gaseous transport
Varying gas-phase atmosphere

ABSTRACT

Transient combustion of a single biomass particle in preheated oxygen and nitrogen atmospheres with varying concentration of oxygen is investigated numerically. The simulations are rigorously validated against the existing experimental data. The unsteady temperature and species concentration fields are calculated in the course of transient burning process and the subsequent diffusion of the combustion products into the surrounding gases. These numerical results are further post processed to reveal the temporal rates of unsteady entropy generation by chemical and transport mechanisms in the gaseous phase of the reactive system. The spatio-temporal evolutions of the temperature, major chemical species including CO, CO_2, O_2, H_2 and H_2O, and also the local entropy generations are presented. It is shown that the homogenous combustion of the products of devolatilisation process dominates the temperature and chemical species fields at low concentrations of oxygen. Yet, by oxygen enriching of the atmosphere the post-ignition heterogeneous reactions become increasingly more influential. Analysis of the total entropy generation shows that the chemical entropy is the most significant source of irreversibility and is generated chiefly by the ignition of volatiles. However, thermal entropy continues to be produced well after termination of the particle life time through diffusion of the hot gases. It also indicates that increasing the molar concentration of oxygen above 21% results in considerable increase in the chemical and thermal entropy generation. Nonetheless, further oxygen enrichment has only modest effects upon the thermodynamic irreversibilities of the system.

Introduction

It is well-established that combustion is, by far, the most irreversible process taking place in thermal power stations [1,2]. Recent studies of coal fired power stations showed that the exergy efficiency of circulating fluidised bed boiler can be lower than 30% [3,4]. This figure clearly reflects the significant role of combustion process in exergetic losses of thermal power generation. Thus, future improvements in power

* Corresponding author.
E-mail address: Nader.Karimi@glasgow.ac.uk (N. Karimi).

https://doi.org/10.1016/j.ijhydene.2018.03.074
0360-3199/

Nomenclature

A	pre-exponential factor, unit vary
A_p	particle surface area, m^2
$a1, a2, a3$	constants
C_D	drag coefficient
c	concentration, $kmol/m^3$
c_p	specific heat capacity, $J/kg\cdot K$
D_{ij}	binary diffusion coefficient for the $i-j$ species pair, m^2/s
$D_{T,i}$	thermal diffusion coefficient for the i^{th} species, m^2/s
D_i	diffusion coefficient of species i, m^2/s
d	diameter, m
e	specific internal energy, J
E	entropy generation rate, W/K
E_a	active energy, J/kmol
E_h	rate of entropy generation due to heat transfer, W/K
E_m	rate of entropy generation due to mass transfer, W/K
E_r	rate of entropy generation duo to chemical reactions, W/K
E'	average entropy generation rate, W/K
F_d	drag force, N
f_h	fraction of heat absorbed by the particle
$\vec{f_i}$	body force per unit mass
$H_{reac_{cr}}$	enthalpy of reaction cr, J/kmol
h	specific enthalpy, J/kmol
h_{fg}	latent heat of devolatilization, J/kg
h'	enthalpy of mixture, J/kmol
g_x	acceleration gravity, m/s^2
$J_{i,j}$	molecular mass flux, $kg/m^3\cdot s$
K	reaction rate, $kmol^{1-(d+e)}/(m^3)^{1-(d+e)}\cdot s$
k_a	rate constant of char combustion reactions, $kmol/m^3\cdot s$
k_c	thermal conductivity, $K\cdot m/W$
k_{cr}	rate constant of reaction cr, $kmol/m^3\cdot s$
k_d	kinetic rate of devolatilization reaction, s^{-1}
Le	Lewis number
M	molecular weight, kg/kmol
$\overline{M}$	average molecular weight, kg/kmol
m	mass, kg
N	number of chemical species
n_{cr}	number of chemical reactions
Nu	Nusselt number
p	pressure, Pa
p^0	reference pressure, Pa
Q_r	internal production rate for thermal energy, J/s
q_j	energy flux
$\vec{q}$	heat-flux vector
$\vec{q_R}$	radiant heat-flux vector
Re	Reynolds number
Ru	universal gas constant, kg/kmol
R_i	net rate of production of species i due to chemical reactions, $kg/m^3\cdot s$
$R_{i,cr}$	chemical production rate for species i, $kmol/m^3\cdot s$
s_E	effective area of entropy generation, m^2
$\vec{s}$	entropy flux vector
s	specific entropy, $J/kmol\cdot K$
s_b	Stefan-Boltzmann constant, 5.67032×10^{-8} $W/m^2\cdot K^4$
T	temperature, K
T^0	reference temperature, K
t	time, s
t_t	effective time of entropy generation, s
u	velocity, m/s
$\vec{u}$	velocity vector
$\vec{V_i}$	diffusion velocity of the i^{th} species
$V'_{i,cr}$	stoichiometric coefficients of the reactants of species i in reaction cr
$V'_{i,cr}$	stoichiometric coefficients of the products of species i in reaction cr
X	mole fraction
Y	mass fraction

Greek Symbols

α	distribution coefficient of volatile in biomass
μ	viscosity, $kg/m\cdot s$
μ_c	specific chemical potential, J/kg
$\overline{\mu_c}$	Molar chemical potential, J/mol
μ_m	molecular viscosity, $kg/m\cdot s$
λ	thermal conductivity, $W/m\cdot K$
ρ	density, kg/m^3
ω_i	rate of species i mass production per unit volume
ε_p	particle emissivity
θ_R	radiation temperature, K
σ	Rate of entropy generation per unit volume, W/m^3K
Φ	viscous dissipation

Subscripts

cr	chemical reaction number
cr'	char reaction number
i	i^{th} species
j	indices: 1,2, …,N
g	gas
p	particle
rg	gaseous reactants
X	composition of chemical element H
Y	composition of chemical element O
x, r	coordinates

Superscripts

$a_{i,cr}$	reaction order of species i in reaction cr
b	temperature exponent
d	reaction order of related gaseous reactants
e	reaction order of oxygen

Please cite this article in press as: Wang L, et al., Gas-phase transport and entropy generation during transient combustion of single biomass particle in varying oxygen and nitrogen atmospheres, International Journal of Hydrogen Energy (2018), https://doi.org/10.1016/j.ijhydene.2018.03.074