DEVELOPMENT OF A SOLID-GAS COUPLED MODEL FOR THERMALLY THICK BIOMASS COMBUSTION IN PACKED BEDS

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DECLARATION

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The above candidate has carried out research for the PhD thesis under my supervision.

Name of the supervisor: Prof. Mahinsasa Narayana

Signature of the supervisor: Date:

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Abstract

The aim of this research is to model the moving grate combustion process by Computational Fluid Dynamics (CFD) method by OpenFOAM software. Kinetic data for heterogeneous reactions, specific to local fuel types is essential. Therefore, pyrolysis kinetics of Rubber and Gliricidia was evaluated by two methods; the sequential approach for Kissinger method and Miura and Maki approach for Ditributed Activation Energy Model (DAEM). The activation energy values obtained by the sequential spproach for Kissinger method are 107.9 kJmol^{-1} for Gliricidia and 83.44 kJmol^{-1} for Rubber wood. Obtained activation energy by Miura and Maki approach for DAEM, varies between 190.57 kJmol^{-1} and 230.58 kJmol^{-1} for Gliricidia and between 111.52 kJmol^{-1} and 179.07 kJmol^{-1} for Rubber wood.

A CFD model was developed which describes the wood combustion in fixed grate type packed bed furnaces. Linear rate of mass loss observed in batch type simulations can be used to describe the steady state burning characteristics of a continuously operated furnace which has a feeding rate equal to burning rate. This mass loss rate was used to evaluate Equivalence Ratio (ER) variation for different particle sizes of wood. A sensitivity analysis was conducted to find the effect of moisture content and particle size on ER. It was found that moisture content of wood has more significant effect on ER than the particle size. The optimum equivalence ratio was studied based on the maximum outlet gas temperature with minimum CO fraction for different particle sizes of wood. The optimum ER values obtained were 0.28 for 25 mm sized particles, 0.13 for 38 mm sized particles and 0.18 for 63 mm sized particles.

The model was elaborated to simulate wood combustion in moving grate type furnaces. This heterogeneous model developed within Eulerian framework, includes the grate movement through boundary conditions, which can solve both bed and free board region simultaneously.

Keywords: Computational Fluid Dynamics, packed beds, combustion, moving grate furnaces

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LIST OF ABBREVIATIONS

Abbreviation	Description
CFD	Computational Fluid Dynamics
DAEM	Distributed Activation Energy Method
DNS	Direct Numerical Simulation
DOM	Discrete Ordinates Model
DPM	Discrete Particles Models
DTM	Discrete Transfer Method
ER	Equivalence Ratio
FVM	Finite Volume Method
FWO	Flynn–Wall–Ozawa
KAS	Kissinger–Akahira–Sunose
LES	Large Eddy Simulation
RANS	Reynolds Averaged Navier-Stokes
RTE	Radiative Transfer Equation
TGA	Thermo Gravimetric Analysis

LIST OF NOMECLATURE

Symbol	Description
A	pre-exponential factor (s^{-1})
A_{spec}	volume specific surface area (m^{-1})
A_p	projected area (m^2)
a_g	absorption coefficient of gas (m^{-1})
a_s	absorption coefficient of solid (m^{-1})
C_i	concentration of gases ($molm^{-3}$)
C_1, C_2	constants used in standard k-epsilon equation
C_{pg}	specific heat capacity of gas ($Jkg^{-1}K^{-1}$)
C_{ps}	specific heat capacity of solid ($Jkg^{-1}K^{-1}$)
$D_{a,I}$	effective diffusivity of species i through ash layer (m^2s^{-1})
D_i	binary diffusivity of species i in air (m^2s^{-1})
$D_{k,i}$	Knudsen diffusivity of species i (m^2s^{-1})
$D_{eff,i}$	effective diffusivity of species i (m^2s^{-1})
d_p	particle diameter (m)
$d_{p,o}$	initial particle diameter (m)
d_{pore}	pore diameter (m)
E	activation energy ($Jmol^{-1}K^{-1}$)
E_p	radiation emission from particles (Wm^{-3})
G	radiation intensity (Wm^{-2})
e	emissivity
$H_{g,i}$	heat of reactions gas phase reactions (Jkg^{-1})
H_m	heat of evaporation (Jkg^{-1})
$H_{s,i}$	heat of reactions solid phase reactions (Jkg^{-1})
h	convective heat transfer coefficient ($Wm^{-2}K^{-1}$)
$h_{m,a,i}$	mass transfer coefficient of i^{th} gaseous component through ash layer (ms^{-1})
h_{mi}	mass transfer coefficient of i^{th} gaseous species in boundary layer (ms^{-1})
$h_{mi,eff}$	effective mass transfer coefficient (ms^{-1})
k	turbulent kinetic energy (m^2s^{-2})

k_i	kinetic reaction rate of char with i^{th} gaseous component (ms^{-1})
$k_{i,eff}$	effective reaction rate (ms^{-1})
l_a	ash layer thickness (m)
M_{air}	air molar weight ($kgmol^{-1}$)
M_c	carbon molar weight ($kgmol^{-1}$)
M_i	species molar weight ($kgmol^{-1}$)
m_0	initial mass of sample (kg)
m_f	final mass of sample (kg)
$m_{s,i}$	mass of solid phase constituents in a computational cell (kgm^{-3})
$m_{s,w}$	mass of water in a computational cell (kgm^{-3})
m	mass (kg)
n	reaction order /refractive index
Nu	Nusselt number
P	pressure (Pa)
Pr	Prandtl number
$Q_{rad,g}$	radiation heat source term ($Jm^{-3}s^{-1}$)
R	universal gas constant ($kJK^{-1}mol^{-1}$)
Re	Reynolds number
$R_{g,i}$	gas phase reaction rate i^{th} species ($kgm^{-3}s^{-1}$)
R_{ki}	gas phase kinetic reaction rate of i^{th} species ($kgm^{-3}s^{-1}$)
$R_{mix,i}$	gas phase mixing rate i^{th} species ($kgm^{-3}s^{-1}$)
$R_{s,i}$	solid phase reaction rate ($kgm^{-3}s^{-1}$)
$R_{s,w}$	rate of drying ($kgm^{-3}s^{-1}$)
$S_{g,i}$	summed production rate of i^{th} gas species in gas phase reactions ($kgm^{-3}s^{-1}$)
Sh	Sherwood number
S_{ij}	turbulent stress tensor (Pa)
S_m	momentum resistance source term ($kgm^{-2}s^{-2}$)
$S_{s,i}$	summed production rate of i^{th} gas species in solid phase reactions ($kgm^{-3}s^{-1}$)
T_{evap}	evaporation temperature (K)
T_g	gas phase temperature (K)

T_s	solid phase temperature (K)
t	time (s)
u	velocity (ms^{-1})
u_{bed}	bed velocity (ms^{-1})
u_{grate}	grate velocity (ms^{-1})
V_{cell}	volume of cells (m^3)
X_a	mass fraction of ash
x	conversion
Y_i	mass fraction of gas species i
Y_b	mass fraction of bound water in solid phase
Y_w	mass fraction of water in solid phase

Greek symbols

α	mass fraction
β	heating rate in pyrolysis kinetic determination/solid cell identification factor shrinkage model
γ	factor of bed height change
ε	turbulent dissipation rate
λ_g	thermal conductivity of gas ($Wm^{-1}K^{-1}$)
λ_s	thermal conductivity of solid ($Wm^{-1}K^{-1}$)
μ	viscosity ($kgm^{-1}s^{-1}$)
μ_t	turbulent viscosity ($kgm^{-1}s^{-1}$)
ρ_a	ash density (kgm^{-3})
ρ_g	gas density (kgm^{-3})
ρ_s	solid density (kgm^{-3})
σ	Steffan Boltzmann constant ($Wm^{-2}K^{-4}$)
$\sigma_{i,air}$	collision diameter (A)
σ_ε, σ_k	model constants in standard k-epsilon equation
σ_s	scattering coefficient
τ	stress tensor (Nm^{-2})

ϕ	porosity
ϕ_a	ash layer porosity
$\Omega_{c,i}$	stoichiometric coefficient of ith heterogeneous reaction
$\Omega_{g,i}$	stoichiometric coefficient of ith gas phase reactions
$\Omega_{c,o}$	stoichiometric coefficient of char oxidation reactions
$\Omega_{g,i,o}$	stoichiometric coefficient of ith gas phase oxidation reaction
$\Omega_{i,air}$	collisional integral

LIST OF APPENDICES