PROCESS PARAMETER OPTIMIZATION OF URBAN BIOWASTE CARBONIZATION

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DECLARATION

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ABSTRACT

About 75% of Municipal solid waste (MSW) collected around the country is organic biomass which mainly includes food waste, wood, paper, saw dust and paddy husk. Urban councils in Colombo city and nearby suburbs collect biowaste separately which has created a huge potential in converting urban biowaste into value-added component like biochar, thus resolving the problems associated with MSW management and mitigating socio-economic and environmental issues related to MSW. In this study, torrefaction is identified as the most viable technology available for the conversion of organic MSW into biochar and the study mainly focuses on developing a three dimensional computational fluid dynamics (CFD) model of a continuous packed-bed torrefaction reactor for organic MSW and then optimizing the process variables and the geometry. A mathematical model including all heat, mass and energy transfers, and heterogeneous & homogeneous reactions is firstly developed and then converted to a numerical model and simulated using OpenFOAM for an insulated cylindrical reactor in which hot gas at elevated temperatures (473 – 623K) is provided from the bottom while solid at ambient conditions is fed from the top. The torrefaction reactor is optimized for gas inlet temperature and residence time and then the geometry of the reactor is optimized for the optimum gas inlet temperature and residence time. Four reaction zones are identified in the reactor domain; i.e. drying, softening & depolymerization, limited devolatilization & carbonization and extensive devolatilization and carbonization. The optimum inlet gas temperature, residence time and D/L ratio are 573K, 13000s and 0.24 respectively. For the optimum conditions, biochar yield is 55.7% while ash content is 19.1%. Further In dry basis, 95.9% of biomass is decomposed and the total weight loss based on the initial wet biomass is 86.6%.

Keywords: Urban biowaste; Biochar; Torrefaction; Computational fluid dynamic; Continuous packed-bed; numerical model

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LIST OF ABBREVIATIONS

Abbreviation	Description
CFD	Computational Fluid Dynamics
MSW	Municipal Solid Waste

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NOMENCLATURE

ρ_g - Density of gas phase (kg m^{-3})

ϵ_g - Volume fraction of gas phase

U_g - Velocity of gas phase (m s^{-1})

μ - Dynamic viscosity (Pa s)

p - Pressure (Pa)

k - Turbulent kinetic energy (m^2 s^{-2})

I - Second order identity tensor

d - Particle size (m)

T_g - Gas phase temperature (K)

T_s - Solid phase temperature (K)

ρ_s - Density of solid phase (kg m^{-3})

ϵ_s - Volume fraction of solid phase

$C_{v,g}$ - Specific heat capacity of gas phase (J kg^{-1} K^{-1})

C_s - Specific heat capacity of solid phase (J kg^{-1} K^{-1})

k_g - Thermal conductivity of gas phase (W m^{-1} K^{-1})

k_s - Thermal conductivity of solid phase (W m^{-1} K^{-1})

$R_{i,hetero}$ - Rate of heterogeneous reaction i (kg m^{-3} s^{-1})

$R_{i,homo}$ - Rate of homogeneous reaction i (kg m^{-3} s^{-1})

Q_R - Radiation heat (W)

h - Heat transfer coefficient (W m^{-2} K^{-1})

A - Specific surface area of bed (m^{-1})

ΔH_i - Enthalpy of the reaction i (J kg^{-1})

$Y_{g,i}$ - Mass fraction of i in the gas phase

$Y_{s,i}$ - Mass fraction of i in the solid phase

$D_{g,i}$ - Diffusion coefficient of i in the gas phase (m^2 s^{-1})

$D_{s,i}$ - Diffusion coefficient of i in the solid phase (m^2 s^{-1})

r_{cel} - Degradation rate of cellulose (kg m^{-3} s^{-1})

r_{hem} - Degradation rate of hemicellulose (kg m^{-3} s^{-1})

r_{lig} - Degradation rate of lignin (kg m^{-3} s^{-1})

f_{cel} - Pre-exponential factor of cellulose decomposition (s^{-1})

f_{hem} - Pre-exponential factor of hemicellulose decomposition (s^{-1})

f_{lig} - Pre-exponential factor of lignin decomposition (s^{-1})

E_{cel} - Activation energy of cellulose decomposition (kJ mol^{-1})

E_{hem} - Activation energy of hemicellulose decomposition (kJ mol^{-1})

E_{lig} - Activation energy of lignin decomposition (kJ mol^{-1})

Y_{cel} - Mass fraction of cellulose

Y_{hem} - Mass fraction of hemicellulose

Y_{lig} - Mass fraction of lignin

$r_{k,O2}$, $r_{k,CO2}$ and $r_{k,H2O}$ - Kinetic reaction rate of char combustion, char CO_2 gasification and char H_2O gasification respectively (kg m^{-3} s^{-1})

f_{O2}, f_{CO2} and f_{H2O} - Pre-exponential factor of char combustion, char CO_2 gasification and char H_2O gasification respectively (m s^{-1} K^{-1})

E_{O2}, E_{CO2} and E_{H2O} - Activation energy of char combustion, char CO_2 gasification and char H_2O gasification respectively (kJ mol^{-1})

M_c, M_{O2}, M_{CO2} and M_{H2O} - Molar mass of char, O_2, CO_2 and H_2O respectively (kg mol^{-1})

v_{O2}, v_{CO2} and v_{H2O} - Stoichiometric coefficient of O_2, CO_2 and H_2O in char combustion, char CO_2 gasification and char H_2O gasification reactions respectively

ρ_{O2}, ρ_{CO2} and ρ_{H2O} - Density of O_2, CO_2 and H_2O in the gas phase respectively (kg m^{-3})

m_{char} - Mass of char per unit volume (kg m^{-3})

$m_{biomass}$ - Initial mass of biomass per unit volume (kg m^{-3})

a - Average stoichiometric coefficient of char in the degradation reactions

A_{ss} - Total specific surface area of solid phase (m^2)

$r_{m,O2}$, $r_{m,CO2}$ and $r_{m,H2O}$ - Mass transfer rate of O_2, CO_2 and H_2O (kg m^{-3} s^{-1})

$\rho_{O2,s}$, $\rho_{CO2,s}$ and $\rho_{H2O,s}$ - Density of O_2, CO_2 and H_2O in the solid surface respectively (kg m^{-3})

$k_{m,O2}$, $k_{m,CO2}$ and $k_{m,H2O}$ - Mass transfer coefficient of O_2, CO_2 and H_2O respectively (m s^{-1})

Sh_i - Sherwood number of i^{th} gas

Sc_i - Schmidt number of ith gas

$D_{i,g}$ - Diffusion coefficient of ith gas (m^2 s^{-1})

Re - Reynolds number

$r_{k,i}$ - Kinetic reaction rate of ith equation (kmol m^{-3} s^{-1})

f_i - Pre-exponential factor of ith equation

E_i - Activation energy of ith equation (kJ mol^{-1})

$[H_2], [O_2], [CO], [H_2O], [CO_2]$and $[CH_4]$ - Concentration of H_2, O_2, CO, H_2O, CO_2 and CH_4 in the gas phase (kmol m^{-3})

$r_{t,i}$ - Turbulent mixing limited reaction rate (kmol m^{-3} s^{-1})

ρ_g - Density of gas (kg m^{-3})

k - Turbulent kinetic energy (m^2 s^{-2})

$\in$ - Turbulent dissipation rate (m^2 s^{-3})

Y_j and Y_k - Mass fraction of reactants of reaction i

v_j and v_k - Stoichiometric metric coefficient of reactants of reaction i

M_j and M_k - Molar mass of reactants of reaction i (kg kmol^{-1})

Q_{sg} - Interphase convective heat transfer rate (W)

A - Specific surface area of solid (m^{-1})

Nu - Nusselt number

Re - Reynolds' number

Pr - Prandtl number

G - Incident intensity (W m^{-2})

a - Absorption coefficient of gas phase (m^{-1})

a_p - Absorption coefficient of solid phase (m^{-1})

n - Refractive index of gas phase

σ - Stefan constant (W m^{-2} K^{-4})

E_p - Equivalent emission of particles

A_r - Specific surface area available for radiation (m^{-1})

ε - Emissivity of solid particles

H_{evp} - Heat of evaporation (kJ kg^{-1} m^{-3})

$Y_{moisture}$ - Mass fraction of moisture

r_d - Drying rate (kg m^{-3} s^{-1})

E_{tor} - Torrefaction heat (kJ m^{-3})

$C_{v,g}$ - Specific heat of gas (kJ K^{-1} kg^{-1})

$R_{biomass}$ - Decomposition rate of biomass (kg m^{-3} s^{-1})

E_{Ri} - Energy released or absorbed due to the reaction i (kJ m^{-3})

r_i - Rate of the reaction i (kmol m^{-3} s^{-1})

H_i - Enthalpy of the reaction I (kJ mol^{-1})