COMPUTATIONAL FLUID DYNAMICS MODELING OF THERMO-CHEMICAL PROCESSES IN AN UPDRAFT BIOMASS GASIFIER

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DECLARATION OF THE CANDIDATE AND SUPERVISOR

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ABSTRACT

Biomass is recently gaining popularity in industry as a promising source of renewable energy. Gasification of biomass is a major thermal conversion method to improve the efficiency of raw biomass fuel. It is a process by which biomass is partially oxidized to produce a combustible gas named Syngas; a mixture of carbon monoxide, hydrogen and methane. Although the gasification technology is used throughout the history and there are a large number of gasification plants worldwide, their smooth operation remains questionable. This is due to a lack of understanding of proper design criteria. In order to gain insights to optimal design parameters, mathematical models and computer simulations based performance analysis can be used. Recently Computational Fluid Dynamics (CFD) analysis has been applied by many researchers as a tool for optimizing packed bed processes including gasification process. In this research study, a two dimensional CFD model has been developed for an updraft biomass gasifier. The model uses air as the gasifying medium and a fixed batch of biomass. The model is capable of tracking the movement of interface between solid packed bed and gas free board due to bed shrinkage. The two phase model is developed using the Euler-Euler approach. The model consists of several sub models, including reaction models, turbulence model for packed bed gas phase and free board, a radiation model for solid phase, a bed shrinkage model, and interphase heat transfer models. The final mathematical model is converted into a numerical model using open source CFD tool OpenFOAM. Required code was developed by using C++ language in OpenFOAM package, including all the relevant differential equations and procedures in the CFD model. To validate the CFD model, simulation results for gas temperature and gas compositions are compared against experimental gas temperatures and compositions measured from an operational laboratory gasifier. The validated model is used to perform air flow rate optimization. A series of CFD simulations were performed for air flow rates ranging from 3 m^3/hr to 10 m^3/hr for a computational geometry corresponding to the experimental gasifier and cumulative CO was calculated. It is found that cumulative CO production maximized at 7 m^3/hr airflow rate. The maximum cumulative CO volume was 6.4 m^3.

Keywords: Biomass, Gasification, Mathematical Model, Computational Fluid Dynamics

DEDICATION

This thesis is dedicated to my beloved mother and to the loving memory of my father

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Niranjan Fernando

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NOMENCLATURE

A	Specific surface area of packed bed (m^{-1})	$r_{i,homo}$	Rate of homogenous reaction i (Kg m^{-3} s^{-1})
A_c	Specific surface area of char (m^{-1})	$r_{m,i}$	Mass transfer limited reaction rate (Kg m^{-3} s^{-1})
A_d	Specific surface area for gas diffusion (m^{-1})	$r_{k,i}$	Kinetic reaction rate (Kg m^{-3} s^{-1})
A_g	Cross sectional area of gasifier (m^2)	$r_{t,i}$	Turbulent mixing limited reaction rate (kg m^{-3} s^{-1})
A_j	pre-exponential factor for heterogeneous reactions (m s^{-1} T^{-1})	Sh_j	Sherwood number for species j
A_r	Specific surface area available for radiation (m^{-1})	$S_\emptyset$	Source term for property $\emptyset$
a	Absorption coefficient of gas phase (m^{-1})	$S_{s,\emptyset}$	Source term for property $\emptyset$ due to solid phase
a_p	Absorption coefficient of solid phase (m^{-1})	$S_{g,\emptyset}$	Source term for property $\emptyset$ due to gas phase
C_g	Heat capacity of gas phase (J $kg^{-1}K^{-1}$)	s_{ij}	Reynolds stress tensor (Pa)
C_s	Heat capacity of solid phase (J $kg^{-1}K^{-1}$)	T_g	Gas phase temperature (K)
$D_{i,g}$	Diffusion coefficient of gas species i (m^2 s^{-1})	$T_{g,in}$	Inlet gas temperature (K)
d	Particle size of biomass (m)	T_s	Solid phase temperature (K)
E_i	Activation energy of reaction i (J mol^{-1})	U_g	Gas phase velocity (m s^{-1})
f_i	Pre-exponential factor of reaction i (s^{-1})	$U_{g,in}$	Inlet gas velocity (m s^{-1})
G	Radiation intensity (W m^{-2})	U_s	Shrinkage velocity (m s^{-1})
h	Heat transfer coefficient (W m^{-2} K^{-1})	v_i	Stoichiometric coefficient of species i
k	Turbulent kinetic energy (m^2 s^{-2})	$Y_{i,g}$	Mole fraction of gas species i
k_g	Thermal conductivity of gas phase (W m^{-1} K^{-1})	$Y_{i,air}$	Mole fraction of i in air
k_s	Thermal conductivity of solid phase (W m^{-1} K^{-1})	$Y_{i,s}$	Mole fraction of solid species i
$k_{m,j}$	Mass transfer coefficient of species j (m s^{-1})	σ	Stefan constant (W m^{-2} K^{-4})
M_i	Molecular weight of species i (Kg mol^{-1})	σ_p	Scattering coefficient of solid particles (m^{-1})
m_i	Density of species i in a computational cell (kg m^{-3})	ϵ	Emissivity of solid particles
Nu	Nusselt number	$\emptyset$	A general transport property
n	Refractive index of gas phase	ε_g	Gas phase fraction
Pr	Prandtl number	ε_s	Solid phase fraction
p	Pressure (Pa)	ρ_g	Density of gas phase (Kg m^{-3})
p_{in}	Inlet pressure (Pa)	ρ_s	Density of solid phase (Kg m^{-3})
Q_{rad}	Radiation heat source (W m^{-3})	ρ_j	Cell density of species j (Kg m^{-3})
Q_i	Initial heat source (W m^{-3})	μ	Dynamic viscosity (Pa s)
Q_{sg}	Convective heat transfer rate (W m^{-3})	$\sigma_{i,air}$	Average collision diameter (A)
q_r	Radiation heat flux (W m^{-2})	$\Omega_{i,air}$	Diffusion collision integral
Re	Reynolds number	ε	Turbulent dissipation rate (m^2 s^{-3})
$R_{g,pyro}$	Rate of release of pyrolytic volatiles (Kg m^{-3} s^{-1})	ΔH_i	Enthalpy of reaction i (J kg^{-1})
r_i	Rate of reaction i (Kg m^{-3} s^{-1})	$\otimes$	Vector outer product
$r_{i,hetero}$	Rate of heterogeneous reaction i (Kg m^{-3} s^{-1})		

LIST OF APPENDICES