Pilot scale Pyrolyser: Compliance and Mechanistic Modeling

A thesis presented in partial fulfillment of the requirement for the degree of

Master of Engineering

In

Chemical and Process Engineering

At Massey University, Palmerston North

New Zealand

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2017

Preface

A pyrolysis reactor was built in a previous project by Bridges et al (2013).The reactor is cylindrical in geometry, with a height of 1000 mm and an internal diameter of 750 mm, it stands vertically. There is a 900 mm tall and 100 mm in diameter perforated core in the center of the reactor. At the base, a combustion chamber provides the hot gases required for heating. The hot gases produced travel up and around the reactor through an annulus region of 11 mm. Heat from the gases is transferred to the reactor wall and then to the wood-chips inside. As drying and pyrolysis reactions occur, gases flow in the same direction as the heat towards the perforated core at the center. Hot pyrolysis gases then flow downwards towards the combustion chamber where they are partially combusted before flowing around the reactor and out the flue stack. This project aimed at mathematically modeling this reactor and also improving the way emissions are released so that it complies with EPA air quality standards.

A mathematical model of an 'open source' pilot-scale pyrolysis reactor was produced to predict the product yield, carbon foot-print, biochar quality and the time taken to achieve complete pyrolysis. A non-equilibrium thermodynamic approach was used which allowed for the use of COMSOL Multi-Physics to solve the model. The Finite Element Method (FEM) was used to solve the system of equations. Pyrolysis kinetics are complex and no single model has yet been widely accepted, therefore simplifications were necessary in this model so that a reasonable solution time could be achieved while producing acceptable results. The model profile of the centre temperature closely followed that of the experimental results and thus the model was considered valid.

In addition, modifications were made to the original design of the pyrolyser in order to improve emissions compliance and improve operations of the pyrolysis. It was important to manage fugitive emissions and completely combust any volatile vapours that would be released into the atmosphere while controlling the operating parameters. In order to achieve this, the following were implemented:

1) The combustion chamber was sealed completely so that no fugitive emissions can escape while limiting the ingress of oxygen.

2) A secondary blower was installed in order to better control the oxygen supply to the burners.
3) The original steel lid, which warped during pyrolysis runs resulting in gaseous leaks, was replaced with a more rigid ceramic lid that doesn't effectively expand when heated.
4) Two 3.4 kW burners were added to the single 3.4 kW burner flare. This gives a total power of 10.2 kW, which is estimated to be enough to completely burn all gaseous products leaving the system.

Acknowledgements

Firstly, I would like to express my gratitude to my supervisor Professor Jim Jones for offering me the opportunity to undertake this master's project and also for his immense patience and understanding, helpful criticism, advice and engagement throughout the project.

Furthermore, I would like to thank my secondary supervisor Dr. Georg Ripberger for all the time and energy he has invested which helped in the successful completion of the project.

I would also like to thank Professor John Bronlund for his advice and guidance and also for allowing me the use of his COMSOL Multi-Physics license, for which without the project would not have been possible.

Lastly, I would like to acknowledge the following people for their help and support throughout the duration of the project; Dr. Gonzalo Martinez Hermosilla, Mr. John Edwards and Mr. Ian Thomas.

Nomenclature

Symbol	Description	Unit	Typical Value
A	Pre-exponential factor	s^{-1}	-
a	Gas volume fraction	-	-
A,B,C	Constants used for calculation of thermal conductivity	$W\ m^{-1}\ K^{-1}$	-
A_l	Liquid contact area of sample	m^2	-
A_w	Water adsorption Coefficient	-	-
c	Concentration	$mol\ m^{-3}$	-
C_P	Specific heat	$J\ kg^{-1}\ K^{-1}$	-
C_{po}	Heat capacity of dry wood	$kJ\ kg^{-1}\ K^{-1}$	
c_{sat}	Saturated volumetric moisture content	%	-
D	Diffusivity co-efficient	$m^2\ s^{-1}$	-
d	Diameter	m	-
ΔT	Temperature difference between the surface and hot gases (T_{ext}-T)	K	-
D_p	Particle diameter	m	
D_w	Water diffusivity	$m^2\ s^{-1}$	-
E	Activation Energy	$kJ\ mol^{-1}$	-
F	Force	N	-
f_C	Fixed carbon content	wt. %	-
G	Specific gravity	-	1.54
g	Acceleration due to gravity	$m\ s^{-2}$	9.81
G_b	Specific gravity	-	-
h	Heat transfer coefficient	$W\ m^{-2}\ s^{-1}$	-
H	Enthalpy of reactions	$kJ\ kg^{-1}$	-
I	Identity matrix	-	-
J	Reaction rate	$mol\ m^{-3}\ s^{-1}$	
k	Kinetic constant	s^{-1}	-
K	Permeability	m^2	-
m	Mass	kg	-
M	Molecular weight	$kg\ mol^{-1}$	-
MC	Moisture content	wt. %	0-30%
MC_{fsp}	Moisture content at saturation	%	-
M_{fsp}	Fiber Saturation point	-	
M_i	Initial mass of sample	kg	-
M_t	mass of sample at time, t	kg	-
P	Pressure	Pa, $kg\ m^{-1}\ s^{-2}$	101325
Pr	Prandtl Number	-	-

Q	Heat generation	W m^{-3}	-
q	Heat flux	W m^{-2}	-
Q_{br}	Mass generation (adsorption/desorption)	kg m^{-3} s^{-1}	-
R	Ideal gas constant	J mol^{-1} K^{-1}	8.314
Ra	Rayleigh number	-	-
Re	Reynold's number	-	-
Sm	Shrinkage of wood	%	-
So	Shrinkage from wet wood to oven dry	%	-
T	Temperature	K	-
u	Darcy velocity	m s^{-1}	-
U	Averaged velocity	m s^{-1}	-
v	Rate of volatilisation	mol m^{-3} s^{-1}	-
VM	Volatile Matter	wt. %	-
x	Final moisture content of wood	%	-
y	Product yield	wt. %	-
y_{fc}	Fixed carbon yield	%	-

Greek Letters

∇	Differential operator given in Cartesian co-ordinates	-
Ω	Coefficient of thermal expansion	K^{-1}
α	Thermal diffusivity	m^2 s^{-1}
ε	emissivity	-
η	Reaction progress variable	-
κ	Thermal conductivity	W m^{-1} K^{-1}
μ	Dynamic Viscosity	Pa s
ρ	Density	kg m^{-3}
σ	Stefan-Boltzmann constant	5.67×10^{-8} W m^{-2} K^{-4}
τ	Turtuosity	-
φ	Porosity	-

Subscript

b	biomass
bed	packed bed of wood chips
c	char
conv	convection
eff	effective
ext	external

fiber	wood fiber
g	non-condensable gases
G	gas phase
i	species
in	inside
L	liquid phase
lw	liquid water
max	maximum
min	minimum
o	outside
P	particle
rs	surface-to-void radiation
rv	surface-to-surface radiation
T	tar
vw	water vapour
w	wood

Table of Contents

Figures

Tables