CFD evaluation of premixed and non-premixed models as suitable representatives of fixed bed biomass combustor freeboard

PRESENTED BY: M. T. L. LEKWANA

SUPERVISED BY: D. M. MADYIRA

CO-SUPERVISED BY: G. A. OOSTHUIZEN

DUE 2015

UNIVERSITY OF JOHANNESBURG

Presentation Outline

- Introduction
- Aim of the Investigation
- Biomass Combustion Process
- Theoretical Background
- Experimental Program
- Experimental Results
- CFD Models
- CFD Results
- Conclusions
- Further Work

UNIVERSITY
OF
JOHANNESBURG

Introduction

- Biomass energy conversion is CO_2 neutral

- There is an established need for net zero Greenhouse gas emissions

- Rural communities of developing countries are dependent on round wood for domestic energy

- Biomass residues from industry, forestry and agriculture can contribute to meeting some of the above mentioned challenges

Aim of Investigation

- The aim is to develop a complete CFD model of a domestic biomass briquette combustor.

- The objectives of the research include:

  - ✓ Capturing the behaviour of the freeboard (gas region)

  - ✓ Capturing the behaviour of the fuel bed (solid-gas region)

  - ✓ Capturing the interaction between the freeboard and the fuel bed

Biomass Combustion Process

1. Drying

This refers to the evaporation of the water content of the fuel particle

2. De-volatilization

This decomposes the dry fuel particle into volatiles (H_2O, CO, H_2, CO_2 and CH_4) and char (C)

3. Homogeneous combustion

Combustion taking place in the freeboard

4. Heterogeneous combustion

Combustion taking place in the fuel bed

UNIVERSITY
OF
JOHANNESBURG

Theoretical Background

- Solid temperature:

$$\frac{\partial\left(\varepsilon\rho_p C_p T_s\right)}{\partial t} = \nabla\left(k_{s,eff}.\nabla T_s\right) + S_s$$

- Solid fraction:

$$\frac{\partial \varepsilon}{\partial t} = -\frac{\omega'''_{c,char}}{\rho_p}\varepsilon$$

- Third power of particle diameter:

$$\frac{\partial d_p^3}{\partial t} = -\frac{\omega'''_{c,char}}{\rho_p}d_p^3$$

UNIVERSITY
OF
JOHANNESBURG

Theoretical Background

- Moisture density:

$$\frac{\partial(\varepsilon\rho_m)}{\partial t} = -\omega_m''' \varepsilon$$

- Dry wood density:

$$\frac{\partial(\varepsilon\rho_w)}{\partial t} = -\omega_w''' \varepsilon$$

- Char density:

$$\frac{\partial(\varepsilon\rho_c)}{\partial t} = \left(\omega_{G,char}''' - \omega_{c,char}'''\right)\varepsilon$$

UNIVERSITY
OF
JOHANNESBURG

Theoretical Background

- Species transport:

$$\frac{\partial}{\partial t}(\rho Y_i) + \nabla . (\rho \bar{v} Y_i) = -\nabla . \overline{J_i} + R_i + S_i$$

- Generalised time averaged scalar conservation:

$$\frac{\partial \varphi}{\partial t} + div(\varphi \bar{v}) = div(\tau_\varphi^* \, grad\varphi) + \left[-\frac{\partial \overline{u'\varphi'}}{\partial x} - \frac{\partial \overline{v'\varphi'}}{\partial y} - \frac{\partial \overline{w'\varphi'}}{\partial z} \right] + S_\varphi$$

- Radiation transfer equation:

$$\frac{dI(\bar{r},\bar{s})}{ds} + (a + \sigma_s)I(\bar{r},\bar{s}) = an^2 \frac{\sigma T^4}{\pi} + \frac{\sigma_s}{4\pi} \int_0^{4\pi} I(\bar{r},\overline{s'})\varphi(\bar{s},\overline{s'})d\boldsymbol{\Omega}$$

UNIVERSITY
OF
JOHANNESBURG

Experimental Program

- The aim of the experimental test:
    - Capturing exit flame temperatures.
    - Determining the fuel mass loss rate.
    - Air inlet velocity

- The fuel used in the test was 200g loose peanut shells.

- Experimental apparatus:
    - Imbaula stove
    - Electronic scale (mass balance)
    - K-type thermocouple
    - Hot wire anemometer

UNIVERSITY
OF
JOHANNESBURG

Experimental Results

Experimental Mass Loss Rate

$$\text{Average mass loss rate} = \frac{\Delta m}{t} = \frac{0.153}{1910} = 0.0000801 \ kg/s$$

Description	Symbol (unit)	Quantity
Initial mass of fuel-combustor system	$m_i \ (\text{kg})$	7.581
Final mass of fuel-combustor system	$m_f \ (kg)$	7.428
Change in mass of fuel-combustor system	$\Delta m (kg)$	0.153
Duration of experiment	$t(s)$	1910

Experimental Results

Temperature and Air Velocity

- Highest measured exit flame temperature: 778.15K

- Average exit flame temperature: 641.15K

- Air inlet velocity: 0.01m/s
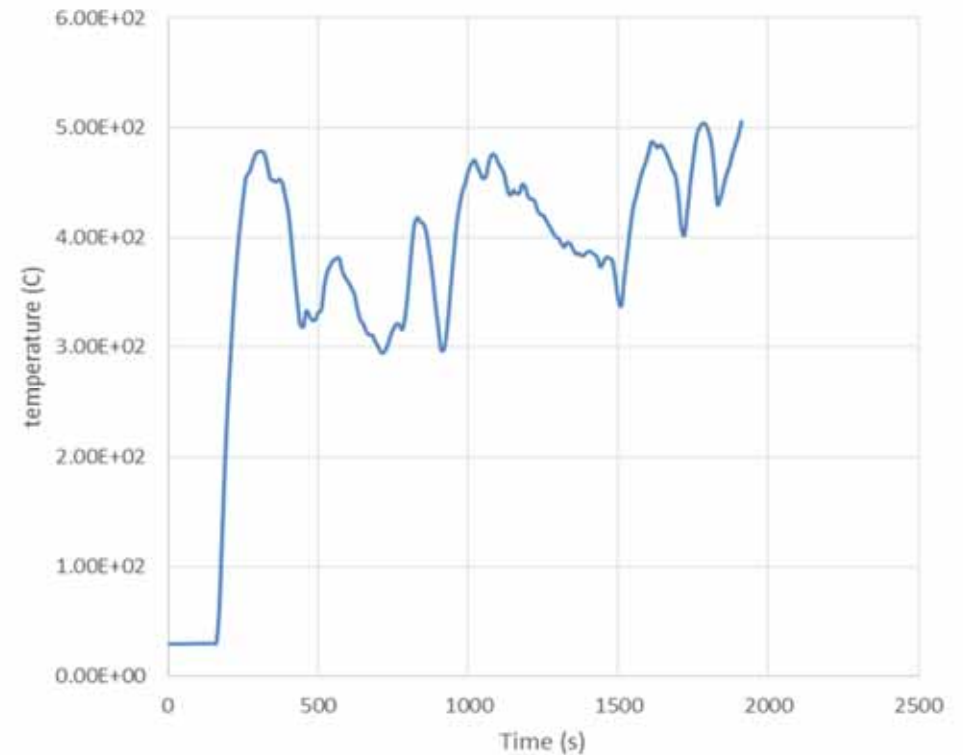
CFD Models

Model Geometry

- The model is a 3D representation of the combustion chamber

- Combustion chamber dimensions:

    - 11cm diameter

    - 25cm depth

- The inlet end is annular with the inner diameter being 2cm

CFD Models

Materials Initially Specified

Boundary	Non-premixed	Premixed
Inlet-air	Species mass fraction: $0.23O_2$ and $0.77N_2$	Species mass fraction: $0.23O_2$ and $0.77N_2$
Inlet-fuel mixture	Species mass fraction: $0.2CH_4$, $0.2H_2$, $0.2CO_2$, $0.2CO$ and $0.2C_6H_6$	Species mass fraction: $0.0162CH_4$, $0.218O_2$, $0.0445CO_2$, $0.0283CO$, $0.079C_6H_6$ and $0.00203H_2$
outlet	Species mas fraction: $0.23O_2$ and $0.77N_2$	Species mass fraction: $0.23O_2$ and $0.77N_2$

CFD Models

Boundary Conditions

Boundary name	Non-premixed	premixed
Inlet-air	- Velocity inlet - Velocities normal to boundary=0.01m/s - Air inlet temperature=300K	- Velocity inlet - Velocity normal to boundary=0.01m/s - Air inlet temperature=300K
Inlet-fuel mixture	- Mass flow inlet - Mass flow rate=0.0000801kg/s - Species inlet temperature=300K	- Mass flow inlet - Mass flow rate=0.0000801kg/s - Species inlet temperature=300K

CFD Models
Boundary Conditions

| Boundary name	Non-premixed	Premixed
outlet	• Pressure outlet • Gauge pressure=0kPa • Backflow total temperature=300K	• Pressure outlet • Gauge pressure=0kPa • Backflow total temperature=300K
Wall	• The wall is stationary • No-slip • Thermal condition specified: adiabatic • Wall thickness=0m	• The wall is stationary • No-slip • Thermal condition specified: adiabatic • Wall thickness=0m

UNIVERSITY
OF
JOHANNESBURG

CFD Models

Model Characteristics

| Model name	Premixed model	Non-premixed model
Radiation model	- Discrete ordinate model - Theta divisions=2 - Phi divisions=2 - Theta pixels=1 - Phi pixels=1 - Non-gray model: off	- Discrete ordinate model - Theta divisions=2 - Phi divisions=2 - Theta pixels=1 - Phi pixels=1 - Non-gray model: off
Viscous model	- Standard k-epsilon model - Standard wall function	- Standard k-epsilon model - Standard wall function
Species model	- Species transport model - Reaction: volumetric - Turbulence-chemistry interaction: eddy dissipation model	- Species transport model - Reaction: volumetric - Turbulence-chemistry interaction: eddy dissipation model

CFD Results

Premixed

Exit flame temperature: 435K

UNIVERSITY
OF
JOHANNESBURG
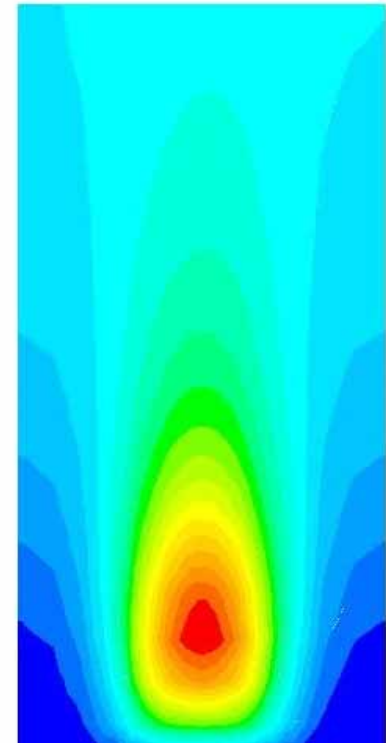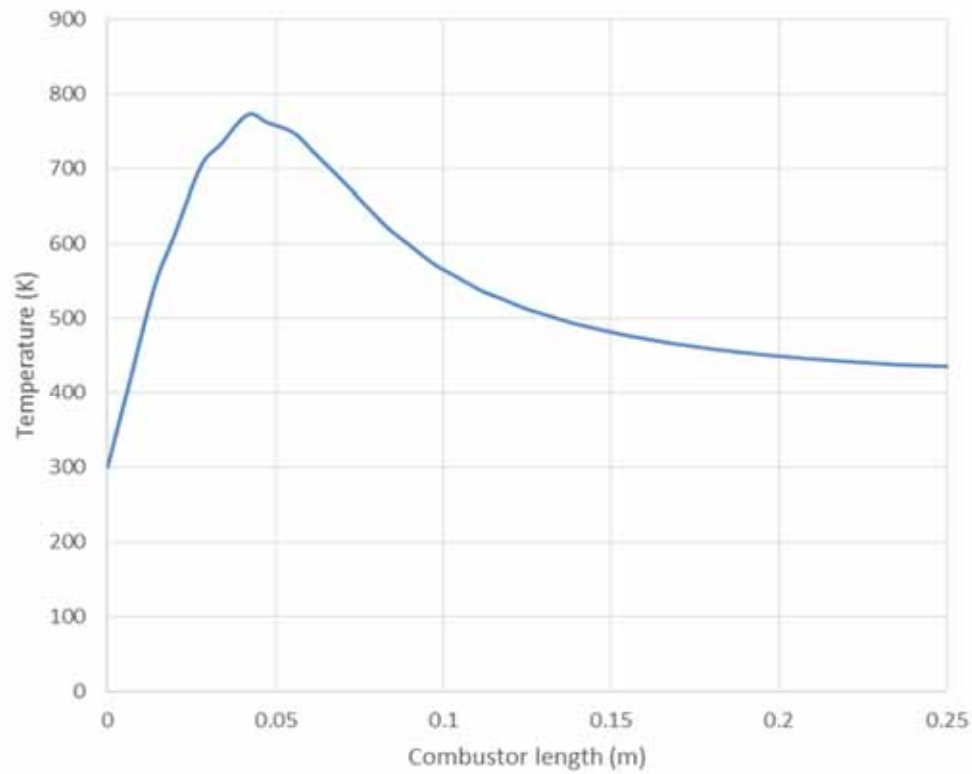
CFD Results

Non-Premixed

Exit flame temperature: 747.9K
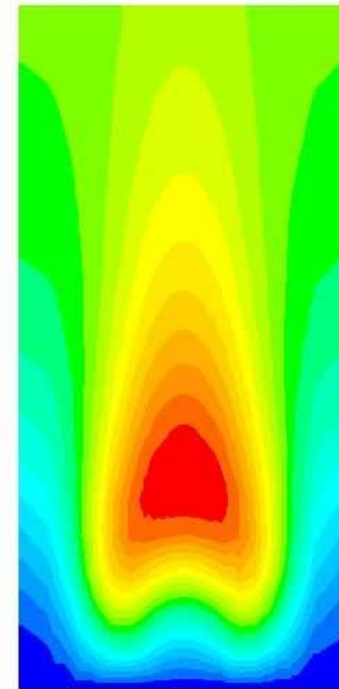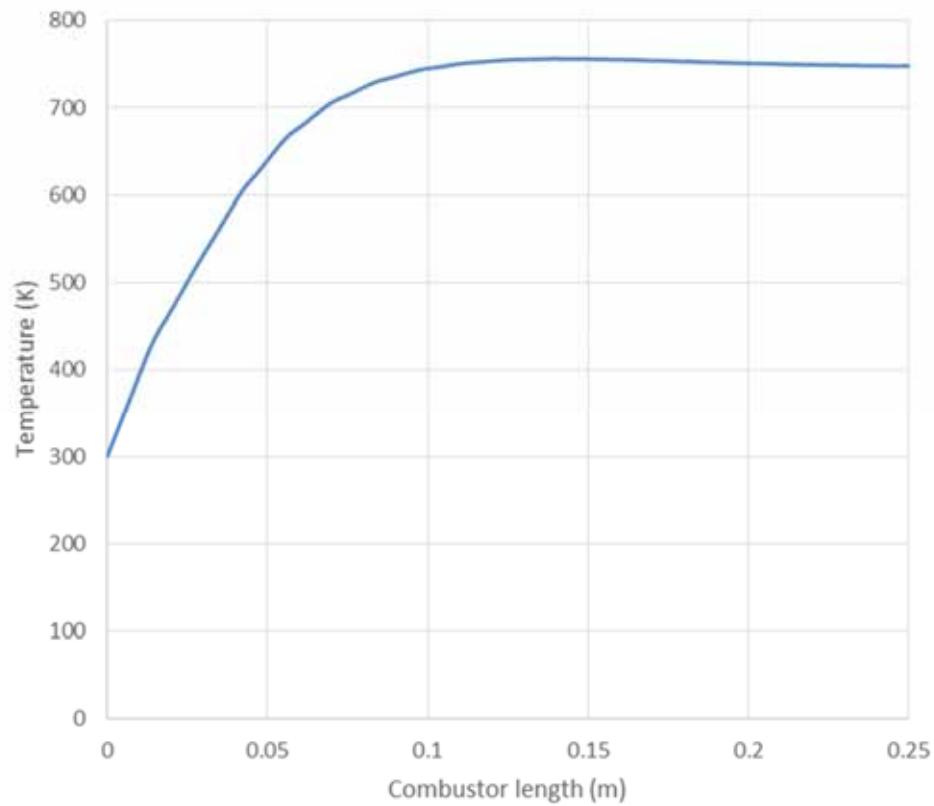
Conclusions

- The noise in experimental exit temperatures necessitated the use of the average temperature as the effective value.

- The percentage difference of the exit flame temperatures between the "effective value" in the experimental case and, respectively, the non-premixed and premixed models is 16.65% and 32.15%.

- This suggests that the freeboard behaviour is better captured by assuming the stream of the fuel and the oxidant to be separate.

- The constant refuelling needed during experiment was confirmation of the high burnout rate of loose biomass.

Future work

- This work is to be followed by the development of a model to represent the behaviour of the fuel bed.

- Together with the above mentioned, efforts will be made to capture the interaction of the freeboard and the fuel bed in order to realize the main goal of the research.

UNIVERSITY
OF
JOHANNESBURG