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

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Presentation Outline

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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

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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

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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:

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

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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:

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

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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:

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

- Radiation transfer equation:

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

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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

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Experimental Results

Experimental Mass Loss Rate

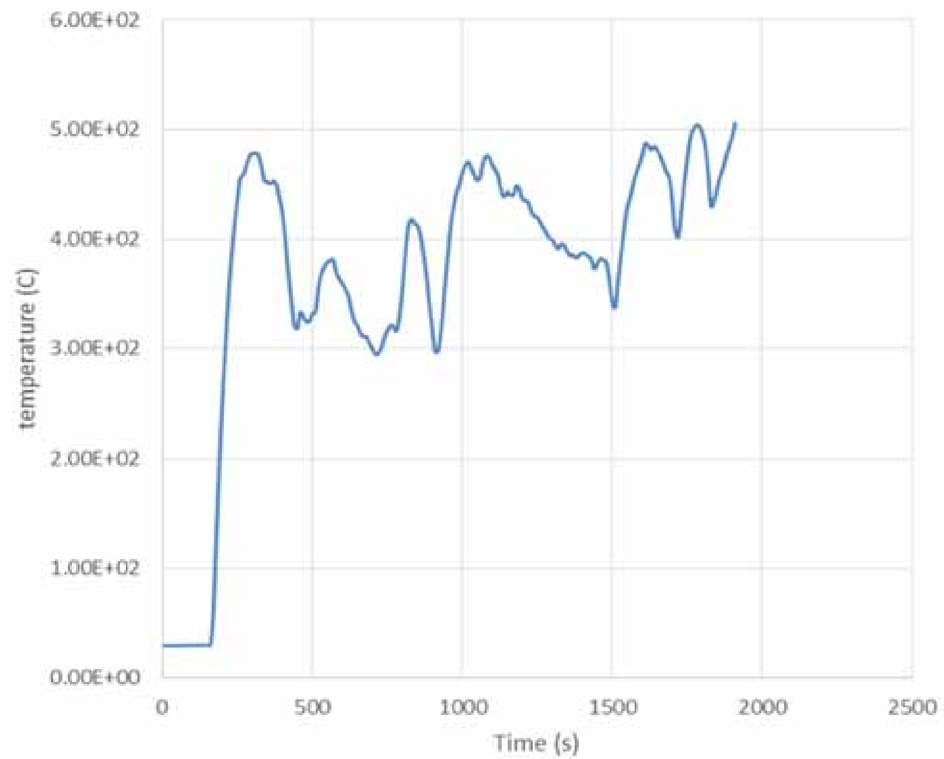
$$Average\ mass\ loss\ rate = \frac{\Delta m}{t} = \frac{0.153}{1910} = 0.0000801\ kg/s$$

Description	Symbol (unit)	Quantity
Initial mass of fuel-combustor system	m_i(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



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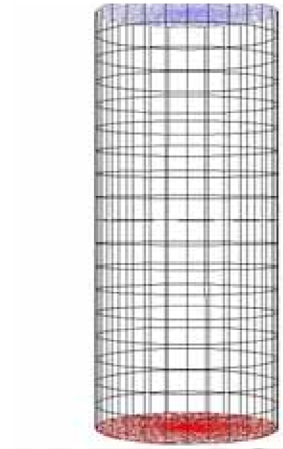
CFD Models

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



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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 $0.77N_2$

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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

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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

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CFD Models

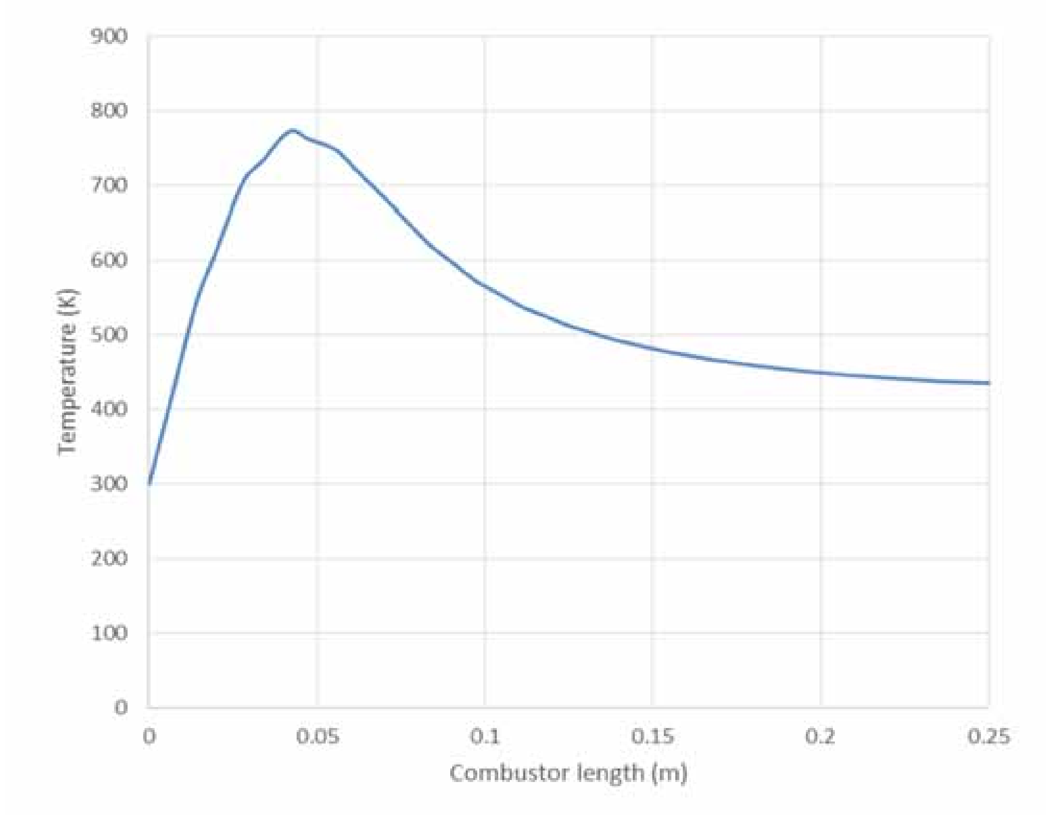
Model Characteristics

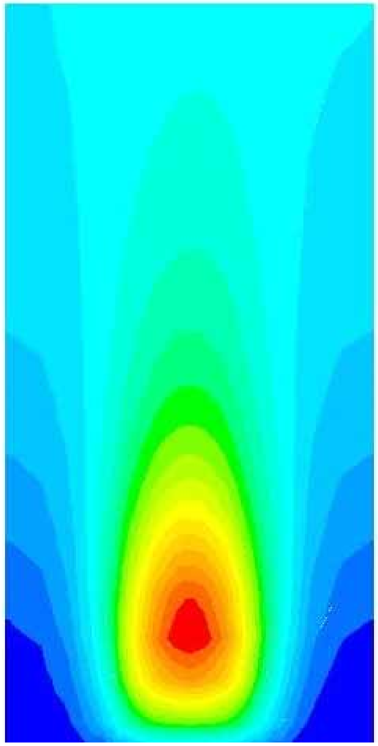
Model name	Premixed model	Non-premixed model
Radiation model	• Discrete ordinate model • Theta divisions=2 • Phi divisions=2 • Theta pixels=1 • Phi pixels=1 • Non-gray model: off	• Discrete ordinate model • Theta divisions=2 • Phi divisions=2 • Theta pixels=1 • Phi pixels=1 • Non-gray model: off
Viscous 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

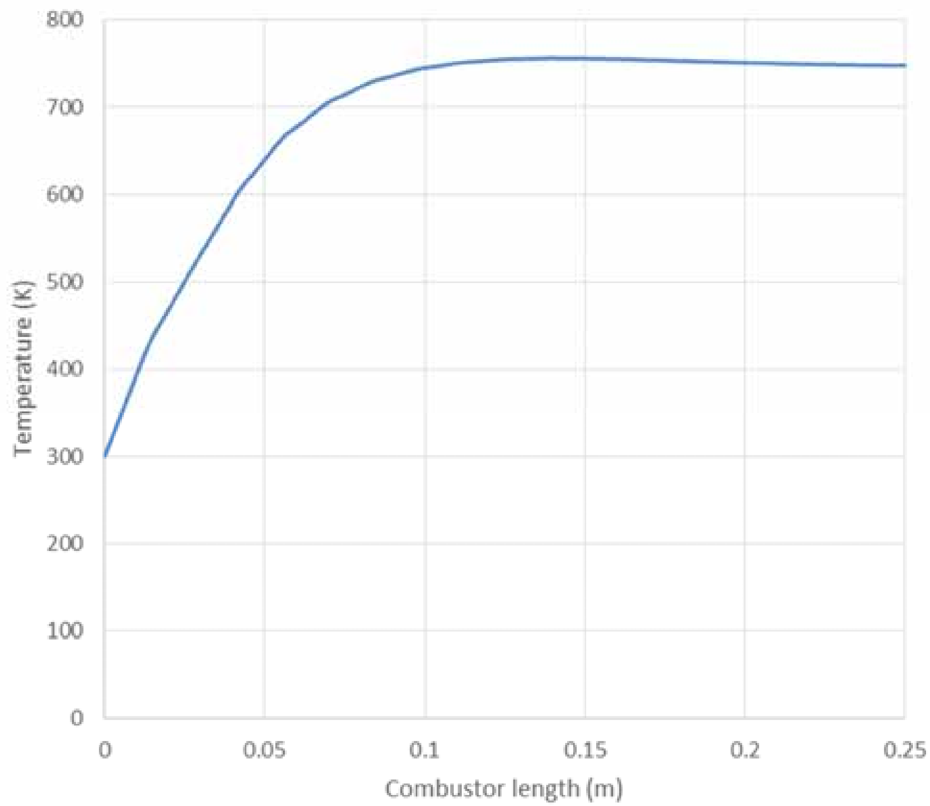


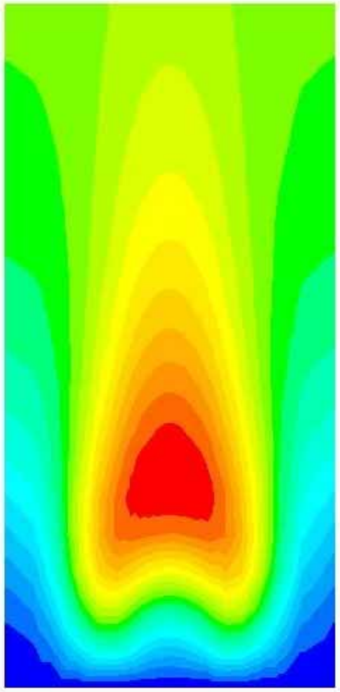


CFD Results

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.

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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.

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