Application of biomass reactivity studies in industrial combustion

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D.Sc. Henrik Tolvanen
M.Sc. Niko Niemelä
Presentation contents

• Why study biomass combustion?
• Phenomena during combustion
• Measurements related to combustion studies
• Kinetics modeling
• Computational fluid dynamics simulations
Significance of fossil fuels

Source: Key World Energy Statistics 2017

1. World includes international aviation and international marine bunkers.
2. In these graphs, peat and oil shale are aggregated with coal.
3. Includes geothermal, solar, wind, heat, etc.
Purpose of reactivity studies

- Predicting
- Designing
- Needs validation

Reactivity studies provide information

Source: Technical University of Munich (TUM)

Source: (S. Black et al., 2013)
Power plant boiler

Power plant boiler

1. Fuel type
2. Particle size
3. Ignition, combustion, flame stability, air / fuel distribution
4. Particle trajectories
5. Corrosion, slagging and fouling
6. Non-combustibles
Biomass diversity

Stages of solid fuel combustion

Solid fuel particle

Drying

Devolatilization, possible shape changes

Char oxidation/gasification

Ash

H₂O

CₙHₙ

CO₂/H₂O

O₂

Char oxidation rate

Devolatilization rate

Drying rate

Mass loss [-]

Time [s]
Test equipment

- One of the most common commercially available devices is **thermogravimetric analysis (TGA)**
- They are well suited for low heating rate experiments
- However, industrial size furnaces always have heating rates several magnitudes higher than in TGA
- **Drop-tube reactor (DTR)** can be used to simulate the temperature level, atmosphere, and especially the heating rate of industrial processes
Thermogravimetric analysis (TGA)

- Weighing device
- Heating elements
- Thermocouple
- Sample and support
- Gas in
- Gas out

\[
\frac{dT}{dt} = 60 \frac{K}{min}
\]

Temperature [K]

Conversion [-]

Time [s]
Drop-Tube Reactor (DTR)

- The particle feeding silo and the collecting vessel can be weighed
- They are weighed before and after feeding
- In this way how much is fed and collected can be easily determined
Drop-Tube Reactor (DTR)

Sample mass loss inside DTR
(Wood 112-125μm)

How to determine the residence time?

Mass loss model

Mass loss measurements

Drop height [cm]
Falling velocity

- A light pulse is shot from the opposing window to the camera
- Two particle shadows in a picture
- Time delay between light pulses, $\Delta t$
- $V_{\text{particle}} = \frac{\Delta x}{\Delta t}$
- Enables residence time determination
Particle size distribution and geometry

CCD high speed camera

Particles scattered on top of glass

Background LED light

Particle projections

Volume fraction \[\frac{V}{V_{tot}}\]

Spherical equivalent diameter [mm]

\[d_{max}\]
\[d_{min}\]
\[A_{projection}\]
\[V_{evaluated}\]
What is needed

- Required Measurement Data for Solid Fuel Reactivity Characterization with drop-tube reactor:
  - Sample mass loss
  - Particle falling velocity
  - Particle surface temperature
  - Size distribution and geometry of the particles
  - Sample elementary analysis
  - Environment data
Environment data

Temperature field inside DTR

*CFD = Computational fluid dynamics
Environment data

Temperature field inside DTR

- Thermocouple measurements
- Thermocouple temperature in CFD
- Gas temperature in CFD

DTR CFD * model

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Particle velocity in the DTR

Particle velocities inside DTR
(Wood 112-125μm)

Velocity [m/s]

Drop height [cm]

Particle velocity measurements
Particle velocity in the DTR

Particle velocities inside DTR
(Wood 112-125μm)

- Particle velocity measurements
- Particle velocities in CFD

Drop height [cm]

Velocity [m/s]
Particle velocity in the DTR

Particle velocities inside DTR
(Wood 112-125µm)

- Particle velocity measurements
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Volume fraction [-]

Diameter [µm]

0% 4% 8%
Kinetics modeling

- Kinetic models try to predict the combustion behaviour of different fuels
- As input they need the fuel reactivity data and also information on the environment
- Reactivity parameters are always fuel specific
- Determining the reactivity parameters from DTR data requires a combined reaction kinetics, heat transfer, and fluid dynamics model
Model complexity

Polynomial fit

\[ m(t) = 1 - (0.61t^4 + 2.6t^3 - 3.8t^2 + 2.4t - 0.02) \]

One reaction pyrolysis model

\[ \frac{dm}{dt} = m_0 k (V_{M_\infty} - VM(t))^m \]

\[ k = A e^{-(E_a/R_T)} \]

Kinetic/Diffusion Surface Reaction Rate Model

\[ \frac{dm_p}{dt} = -\pi d_p^2 \frac{p_{ox}}{D_0 + R} \]

Correlation model

\[ T_{gas} = 900°C \]
\[ T_{gas} = 850°C \]
\[ T_{gas} = 700°C \]

Phenomenon model

Conversion [s]

Time [s]

Conversion [s]

Time [s]

Conversion [s]

Time [s]
Strategy

Experimental Tests
Strategy

Experimental Tests

↓

CFD Model of the test rig
Strategy

Experimental Tests

CFD Model of the test rig

Optimization program
Strategy

Experimental Tests

↓

CFD Model of the test rig

Optimization program

Comparison to measured data

→ Validation

Reactivity parameters, particle shape factors, etc.

Larger scale CFD simulations
Strategy

Experimental Tests

CFD Model of the test rig

Optimization program

Error of e.g. 10% in particle density

Reactivity parameters, particle shape factors, etc.

Error?

Industrial processes

Larger scale CFD simulations
Larger scale CFD simulations

50 kW Test Reactor in Dresden Technical University

Lignite particle (50 μm) trajectories and temperature history

1300°C

50°C
Larger scale CFD simulations

Lignite

- 1110°C
- 1040°C
- 960°C
- 830°C
- 770°C
- 0.3 m

Biomass

- 1231°C
- 1080°C
- 1050°C
- 1000°C
- 860°C
- 800°C

Model vs measurements

Temperatures at different radial positions for Lignite and Biomass, showing a comparison between model predictions and measurements.

Radial position [m] vs Temperature [°C] graphs for Ports 1 to 6.
Larger scale CFD simulations

Biomass combustion tests at Technical University of Munich, 120 kW Reactor

• Gas composition
• Temperature profile
• Particle samples from flame
• High speed video imaging of the flame
• Data compared to CFD results → Validation
Thank you for your attention!

Contact information:

D.Sc. Henrik Tolvanen
henrik.tolvanen@tut.fi
+358 408616718

M.Sc. Niko Niemelä
niko.p.niemela@tut.fi
+358 408381434