CHARACTERIZATION OF AN ENTRAINED FLOW REACTOR FOR PYROLYSIS/GASIFICATION OF COAL AND BIOMASS

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Motivation for high temperature and high pressure biomass co-firing

Advantages/Disadvantages of Increased temperature & pressure

Purpose: Determine effects of increased temperature and pressure on the reaction rates and product composition of pyrolysis/gasification of coal, biomass and their blends

Design features of the high pressure-high temperature entrained flow reactor

Reaction kinetics and char properties at atmospheric pressure

Summary and future works
Ultra clean synthesis gas required for conversion to liquid. Gasification & Gas cleaning remain the main burdens.

(Foust, 2008)
High temperature gasification (1300-1600 °C) produces a gas with low concentration of undesired products (tar, CH$_4$)

→ Gas cleaning cost reduction

High pressure gasification (15-60 bar) provides a better efficiency for gas to liquid conversion

→ Plant size reduction and subsequent processing cost reduction

• High potential for cost reduction if high temperature, high pressure gasification is well understood
Effect of temperature on gas composition

(a) Equilibrium gas composition of Oxygen-Steam gasification at 1 bar, H/O = 1: (a) Pittsburgh #8 (b) Switchgrass
Tchapda & Pisupati (2011)
Effects of temperature & pressure on gas composition

Effect of pressure on gas composition

Tchapda & Pisupati (2011)
MOTIVATION

Cold Gas Efficiency vs Temperature and pressure

Calorific Value vs Temperature and pressure

Tchapda & Pisupati (2011)
Effect of Pressure, Temperature and gaseous environment (CO₂, H₂O, O₂) on:

- Organics and in-organics of fuels (Coal, Biomass, Coal & Biomass blends) under Pyrolysis, Gasification, and Combustion conditions
- Kinetics of thermal decomposition of coal, biomass, coal and biomass blends
- Pressure: 30 bar max
- Temperature: 1600 °C max
- Reaction zone length: 2 m
- Coal feed rate: up to 5 g/min
- Reactor Tube Diameter: 63 mm
- Overall Height of reactor: 5 m
- Maximum Power Input: 38 kW (reactor) + 6 kW (preheater)
- Online monitoring of reaction processes
- Coal & Biomass Powder Feeders
DESIGN FEATURES

- Top + Fuel injection system
- Body Under construction (removable)
- Bottom + Char/Ash Collection system
- Preheater
DESIGN FEATURES

Hopper

Mixing Nozzle

Fuel feeding system
Simplified 3D representation for modeling purposes

Steady state coupled fluid flow and heat transfer with radiation

COMSOL Multiphysics
Shell temperature as high as 330 °C (600 K)
Cooling of reactor vessel necessary
Coal and biomass pyrolysis:
- Pittsburgh #8 ($d_p$ 45 – 75 μm)
- Switchgrass ($d_p$ 105 – 250 μm)

- 1573 K, 1673 K and 1773 K
- Reaction gas: CO$_2$ 30g/min
- Transport gas: CO$_2$ 10 g/min
- Coal flow rate: 1.5 g/min
- Biomass flow rate: 1 g/min
- Thimble filter maintained at 300°C
- Tar collected in the tar collection train
- Light gases sent to the GC for analysis
Particle velocity

\[
\frac{dV_p}{dt} = \frac{18\mu}{\rho_p d_p^2} (V_g - V_p) f(R_{ep}) + \left(1 - \frac{\rho_g}{\rho_p}\right) g
\]

\[
V_p = V_g + \left(V_p^* - V_g\right) e^{-A \Delta t} + \frac{\tau_v \left(1 - \frac{\rho_g}{\rho_p}\right) g}{f(R_{ep})} \left(1 - e^{-A \Delta t}\right)
\]

\[
A = \frac{f(R_{ep})}{\tau_v}, \quad \tau_v = \frac{\rho_p d_p^2}{18\mu}
\]

Residence time:
Coal: 0.5 s  Biomass: 0.7 s
**Particle temperature**

\[ m_p C_{p,p} \frac{dT_p}{dt} = h_{conv}A_p (T_g - T_p) + \epsilon_p A_p \sigma (\theta_R^4 - T_p^4) + \frac{dm_p}{dt} \Delta H_{dvol} \]

\[ T_p = \frac{C_4}{C_3} \left[ 1 - e \left( -\frac{C_3 \Delta t}{m_p C_{p,p}} \right) \right] + T_p^* e \left( -\frac{C_3 \Delta t}{m_p C_{p,p}} \right) \]

\[ C_1 = h_{conv} \ast A_p \]

\[ C_2 = \epsilon_p \ast \sigma \ast A_p \]

\[ C_3 = C_1 + C_2 T_P^3 \]

\[ C_4 = C_1 \ast T + C_2 \theta_R^4 + \frac{dm_p}{dt} \Delta H_{dvol} \]
Switchgrass at Atmospheric Pressure

Sum of species equals mass loss: \( \sum_{i}^{n} \frac{k_i}{k} = 1 \)

<table>
<thead>
<tr>
<th>T(K)/</th>
<th>473</th>
<th>673</th>
<th>873</th>
<th>1073</th>
<th>1273</th>
<th>1473</th>
<th>1500</th>
<th>1573</th>
<th>1673</th>
<th>1773</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\Sigma k_i)</td>
<td>1.77E+78</td>
<td>2.10E+44</td>
<td>8.89E+25</td>
<td>2.75E+14</td>
<td>3.67E+06</td>
<td>8.34</td>
<td>2.85</td>
<td>1.42</td>
<td>1.8</td>
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<tr>
<td>k</td>
<td>0.116</td>
<td>0.454</td>
<td>0.951</td>
<td>1.512</td>
<td>2.079</td>
<td>2.62</td>
<td>2.69</td>
<td>2.88</td>
<td>3.13</td>
<td>3.36</td>
</tr>
<tr>
<td>(\Sigma k_i / k)</td>
<td>1.52E+79</td>
<td>4.64E+44</td>
<td>9.35E+25</td>
<td>1.82E+14</td>
<td>1.76E+06</td>
<td>3.18</td>
<td>1.06</td>
<td>0.49</td>
<td>0.58</td>
<td>0.77</td>
</tr>
</tbody>
</table>
- Excellent prediction of species formation and mass loss at higher temperatures
- Some expected species (N containing compounds: NH$_3$ & HCN) not detected by the GC
Coal char density still higher despite higher conversion of biomass
React kinetic model with BET surface area for Pittsburgh #8:

- **1300 C**: 61.5 m²/g
- **1400 C**: 64.7 m²/g
- **1500 C**: 21.9 m²/g
Pittsburgh #8 @ 1500 C

BET Surface area ($N_2$) 21.9 $m^2/g$

Pore coalescence
Low reactivity of high temperature coal chars
Deactivation of coal char initiated at temperature > 1300 C

TGA reactivity in CO$_2$ at 800 C: Coal char
Low reactivity of high temperature biomass chars
Deactivation not observed with biomass chars

TGA reactivity in CO$_2$ at 800 C: Biomass char
SUMMARY

- High pressure entrained flow reactor design, modeled
- Pyrolysis section of the reactor built and operated
- Pyrolysis experiments carried out at atmospheric pressure
- Kinetics parameters for coal and biomass conversion at high temperature in CO₂ derived and validated at atmospheric pressure
- Conclusion:
  - Visible coalescence of coal char observed at 1500°C
  - Coal and biomass chars obtained at high temperature have low reactivity
  - Deactivation of coal chars initiated at temperature > 1300°C
  - Deactivation not observed in biomass chars
ONGOING AND FUTURE WORKS

- Complete the pyrolysis experiments at higher pressure (10 bar and 20 bar)
- Complete the construction of the gasification reactor (reactor body)
- Derive and validate kinetic parameters for coal, biomass and their blends at higher pressure
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