Co-gasification of Blended Coal with Feedlot and Chicken Litter Biomass

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Fixed-Bed Gasification: Overall Process

1. **Fuel Preparation**
   - Collection, drying, grinding, and size classification

2. **Fixed-Bed Gasification**
   - Fuel feed rate, sample gas conditioning
   - Air flow, fixed-bed temperature, bed-height, pressure
   - Product gas composition, gasification zones, ash agglomeration, A/F

3. **Process Monitoring**

4. **Analysis**

5. **Gas Cleanup**
   - Tar removal

6. **Exhaust**

Inputs:
- Biomass: Feedlot manure, chicken litter
- Coal

Outputs:
- Product gas
- Exhaust
Biomass Generation and Collection

Feedlot Biomass (FB)
- Generation
- Collection
- Transportation
- Stockpile (windrows)

Chicken Litter (LB)
- Generation
- Collection (cleanout)

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Texas A & M UNIVERSITY
Fuel Preparation

- **Dried Uncrushed Fuel** (10-20%, Moisture)
- **Feedlot Biomass**
- **Coal**
- **Chicken litter**

Blending (equal parts by mass):

- **Blend**: 50:50, Coal: Biomass
## Fuel Properties: Proximate Analysis

<table>
<thead>
<tr>
<th>Fuel</th>
<th>%DL</th>
<th>%VM</th>
<th>%FC</th>
<th>%Ash</th>
<th>HHV&lt;sup&gt;a&lt;/sup&gt;</th>
<th>HHV&lt;sup&gt;b&lt;/sup&gt;</th>
<th>HHV&lt;sup&gt;b&lt;/sup&gt;/ kg of O&lt;sub&gt;2&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>21.2</td>
<td>32.6</td>
<td>41.9</td>
<td>4.3</td>
<td>27.7</td>
<td>28.9</td>
<td>15.3</td>
</tr>
<tr>
<td>AFB (Advanced Feedlot Biomass)</td>
<td>10.9</td>
<td>57.0</td>
<td>17.3</td>
<td>14.8</td>
<td>16.8</td>
<td>19.7</td>
<td>19.2</td>
</tr>
<tr>
<td>LB (Chicken Litter Biomass)</td>
<td>7.5</td>
<td>40.3</td>
<td>8.4</td>
<td>43.8</td>
<td>10.0</td>
<td>17.8</td>
<td>19.6</td>
</tr>
<tr>
<td>CAFB (Coal: Advanced Feedlot Biomass, 50:50)</td>
<td>16.1</td>
<td>44.8</td>
<td>29.6</td>
<td>9.6</td>
<td>21.9</td>
<td>24.2</td>
<td>17.0</td>
</tr>
<tr>
<td>CLB (Coal: Advanced Feedlot Biomass, 50:50)</td>
<td>14.4</td>
<td>36.4</td>
<td>25.2</td>
<td>24.1</td>
<td>18.1</td>
<td>23.8</td>
<td>17.6</td>
</tr>
</tbody>
</table>

<sup>a</sup> Dry basis, <sup>b</sup> Dry ash free basis
## Fuel Properties: Ultimate Analysis

<table>
<thead>
<tr>
<th>Fuel</th>
<th>%C</th>
<th>%H</th>
<th>%O</th>
<th>%N</th>
<th>%S</th>
<th>AF*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>58.9</td>
<td>6.2</td>
<td>33.8</td>
<td>0.9</td>
<td>0.3</td>
<td>8.1</td>
</tr>
<tr>
<td>AFB (Advanced Feedlot Biomass)</td>
<td>43.7</td>
<td>6.2</td>
<td>44.9</td>
<td>4.0</td>
<td>0.8</td>
<td>4.4</td>
</tr>
<tr>
<td>LB (Chicken Litter Biomass)</td>
<td>39.1</td>
<td>6.7</td>
<td>48.3</td>
<td>4.7</td>
<td>1.2</td>
<td>3.9</td>
</tr>
<tr>
<td>CAFB (Coal: Advanced Feedlot Biomass, 50:50)</td>
<td>51.7</td>
<td>6.4</td>
<td>39.0</td>
<td>2.4</td>
<td>0.5</td>
<td>6.1</td>
</tr>
<tr>
<td>CLB (Coal: Advanced Feedlot Biomass, 50:50)</td>
<td>51.6</td>
<td>6.4</td>
<td>39.1</td>
<td>2.3</td>
<td>0.6</td>
<td>5.8</td>
</tr>
</tbody>
</table>

* Stoichiometric air fuel ratio (mass basis), dry ash free basis
Gasification Set up

TAMU Fixed-Bed Gasifier (10 kW)

1. Fixed-bed gasifier
2. Fuel feeding system
3. Primary air supply system
4. Set up pre-heat system
5. Fixed-bed pressure regulator
6. Product gas cleaning system
7. Temperature data recorder
8. Sampling gas conditioning system
9. Offline gas analysis (GC)
Operation

For each type of fuel with a given particle size distribution:

- Adjust primary air flow rate (1.48, 1.97 kg/h).
- Preheat to 530 K using propane torch in Plenum Chamber.
- Drop fuel (0.3 kg), continue heating until bed $T_{bed} \sim 1100$ K, stop external heating.
- Keep adding fuel until Bed height $\sim 17$ cm (approx. 20 min).
- Take measurements (Temp, Gas species).
- Run for approximately 1 hour (bed ht. at 17 cm).
- Stop air flow, allow system to cool for 24 h, remove ash from the bed (study agglomeration, if any).
### Gasification Parameters

#### Fuels gasified:

<table>
<thead>
<tr>
<th></th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Coal</td>
</tr>
<tr>
<td>2</td>
<td>Coal: AFB (50: 50%, wt) (CAFB)</td>
</tr>
<tr>
<td>3</td>
<td>Coal: LB (50: 50%, wt) (CLB)</td>
</tr>
<tr>
<td>4</td>
<td>Coal: HFB (50: 50%, wt) (CHFB)</td>
</tr>
<tr>
<td>5</td>
<td>Advanced Feedlot Biomass (AFB): low ash</td>
</tr>
<tr>
<td>6</td>
<td>Soil-Surfaced Feedlot Biomass (SSFB): very high ash</td>
</tr>
<tr>
<td>7</td>
<td>Chicken Litter Biomass (LB)</td>
</tr>
<tr>
<td>8</td>
<td>High-Ash Feedlot Biomass (HFB): 70% SSFB + 30% FB</td>
</tr>
<tr>
<td>9</td>
<td>LB: HFB (50: 50%, wt) (LHFB)</td>
</tr>
</tbody>
</table>

#### Gases Measured:

- CO, CO₂, H₂, CH₄, C₂H₄, C₂H₆, N₂, O₂

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary Air air flow rate</td>
<td>1.48 &amp; 1.7 kg/h (A &amp; B)</td>
</tr>
<tr>
<td>Primary Air Temp</td>
<td>300 K</td>
</tr>
<tr>
<td>Fuel Bed Height</td>
<td>~ 17 cm</td>
</tr>
<tr>
<td>Gasifier Pre-Heat Temp</td>
<td>530 K</td>
</tr>
<tr>
<td>Fuel Feed Rate</td>
<td>Varies</td>
</tr>
<tr>
<td>Fuel Particle Size</td>
<td>~ 5, 10 mm (1 &amp; 2)</td>
</tr>
<tr>
<td>Duration of Experiment</td>
<td>~1 h + preheat period</td>
</tr>
</tbody>
</table>

### Parametric Studies:

- **Air flow rate:** 1.48, 1.97 kg/h
- **Nominal dia. of particles:** 5.15±1.15, 9.4±3.1 mm
- **C-1-A:** (Coal - dₚ = 9.4 mm - m_air = 1.48 kg/h)
Temperature Profile: Coal-2-A

$x_{t^*=0}^* = 0.602, \; x_{t^*=1.0}^* = 0.165, \; \Delta x^* = 0.437$

$T_{t^*=0}^* = 1500 \text{ K}, \; T_{t^*=1.0}^* = 1388 \text{ K}, \; \Delta T^* = 112 \text{ K}$

Coal-2-A (Coal, 5.15 mm, 1.48 kg/h), ash = 4.3%
Comparative Temperature Profile

\[ x_{t=0}^* = 0.115, \quad x_{t=1.0}^* = 0.308, \quad \Delta x^* = 0.193 \]

CAFB-2-A (CAFB, 5.15 mm, 1.48 kg/h)
Ash: 9.6%

CLB-2-A (CLB, 5.15 mm, 1.48 kg/h)
Ash: 24.1%

\[ T_{t=0}^* = 1315 \text{ K}, \quad T_{t=1.0}^* = 1046 \text{ K}, \quad \Delta T^* = 269 \text{ K} \]

\[ T_{t=0}^* = 1227 \text{ K}, \quad T_{t=1.0}^* = 752 \text{ K}, \quad \Delta T^* = 475 \text{ K} \]
Non Dimensional Temperature Profiles

\[ \eta = \frac{x^*}{\sqrt{t^*}} \]

\[ x^* = x / H, \text{ where } H = 0.17m \text{ (fixed-bed height)} \]

\[ t^* = \frac{t-t_0}{t_c}, \text{ where } t_0 = \text{time required to achieve initial bed height (H)} \]

\[ t_c = \text{total time into run} \]

\[ R^2_{\text{CLB}} = 0.92 \]
\[ R^2_{\text{CAFB}} = 0.92 \]
\[ R^2_{\text{Coal}} = 0.95 \]
Oxidation-Front Propagation Velocity in the Fuel-Bed

\[
\frac{v_{pk,ave}}{v_{air}} = \frac{\pi}{6} G_{gas}
\]

\[
G_{gas} = \left(\frac{\rho_{air}}{\rho_{ash}}\right) \left(\frac{Y_{O2}}{Y_{O2}}\right) \left(\frac{Y_{ash}}{1-Y_{VM}-Y_{M}}\right)
\]

\[R^2_{Ggas} = 0.85\]
Oxidation-Front Propagation Velocity in the Fuel-Bed

\[
\frac{v_{pk,ave}}{v_{air}} = \frac{\pi}{6} G_{gas}, \quad \Rightarrow \quad \left( \frac{v_{pk,ave}}{v_{air}} \right) \propto G_{gas}, \quad \text{where} \quad G_{gas} = \left( \frac{\rho_{air}}{\rho_{ash}} \right) \left( \frac{Y_{O_2}}{v_{O_2}} \right) \left( \frac{Y_{ash}}{1-Y_{VM}-Y_{M}} \right)
\]

\( G_{gas} \) is the non-dimensional gasification group

Gas species measurements at \( x^* = 0.074 \)

<table>
<thead>
<tr>
<th>% Vol. (dry basis)</th>
<th>Initial readings ((t^* \sim 0.08 \text{ h}))</th>
<th>Reading at the end of the experiment ((t^* \sim 1.0 \text{ h}))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C-2-B</td>
<td>CAFB-2-B</td>
</tr>
<tr>
<td>( \text{H}_2 )</td>
<td>5</td>
<td>1.3</td>
</tr>
<tr>
<td>( \text{O}_2 )</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>( \text{N}_2 )</td>
<td>63.6</td>
<td>69.3</td>
</tr>
<tr>
<td>( \text{CO} )</td>
<td>25.5</td>
<td>26.9</td>
</tr>
<tr>
<td>( \text{CH}_4 )</td>
<td>0.7</td>
<td>0</td>
</tr>
<tr>
<td>( \text{CO}_2 )</td>
<td>5.2</td>
<td>2.6</td>
</tr>
</tbody>
</table>
Different Zones in the Fixed-Bed

Combustion:
\[ \frac{d\theta}{d\eta} > 0 \]
\[ \frac{d^2\theta}{d\eta^2} < 0 \]

Gasification:
\[ \frac{d\theta}{d\eta} < 0 \]
\[ \frac{d^2\theta}{d\eta^2} < 0 \]

Drying and Devolatilization:
\[ \frac{d\theta}{d\eta} < 0 \]
\[ \frac{d^2\theta}{d\eta^2} > 0 \]

Oxidation front:
\[ (T_{\text{peak}}) \]

Gasification front:

Oxidation – front location:
- Coal: 0.11
- CAFB: 0.31
- CLB: 0.44

Gasification – front location:
- Coal: 0.49
- CAFB: 0.65
- CLB: 0.85

\[ \eta = \frac{x^*}{\sqrt{t^*}} \]
### Product Gas Composition

<table>
<thead>
<tr>
<th>Fuel</th>
<th>% H₂</th>
<th>% CO₂</th>
<th>% CO</th>
<th>% CH₄</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-1-A</td>
<td>8.1</td>
<td>1.9</td>
<td>27.2</td>
<td>1.8</td>
</tr>
<tr>
<td>C-1-B</td>
<td>8.9</td>
<td>3.3</td>
<td>28.8</td>
<td>2.2</td>
</tr>
<tr>
<td>C-2-A</td>
<td>8.6</td>
<td>2.5</td>
<td>25.6</td>
<td>2.1</td>
</tr>
<tr>
<td>C-2-B</td>
<td>8.7</td>
<td>3.1</td>
<td>29.3</td>
<td>2.3</td>
</tr>
<tr>
<td>CAFB-1-A</td>
<td>8</td>
<td>6</td>
<td>28.1</td>
<td>2.2</td>
</tr>
<tr>
<td>CAFB-1-B</td>
<td>8.8</td>
<td>4.8</td>
<td>29</td>
<td>1.6</td>
</tr>
<tr>
<td>CAFB-2-A</td>
<td>9.9</td>
<td>4</td>
<td>29.5</td>
<td>2.1</td>
</tr>
<tr>
<td>CAFB-2-B</td>
<td>9.2</td>
<td>4.5</td>
<td>30</td>
<td>1.8</td>
</tr>
<tr>
<td>CLB-1-A</td>
<td>10.1</td>
<td>4.8</td>
<td>28.7</td>
<td>1.9</td>
</tr>
<tr>
<td>CLB-1-B</td>
<td>7.7</td>
<td>2.9</td>
<td>29.5</td>
<td>1.7</td>
</tr>
<tr>
<td>CLB-2-A</td>
<td>8.5</td>
<td>4.3</td>
<td>30</td>
<td>1.8</td>
</tr>
<tr>
<td>CLB-2-B</td>
<td>7.8</td>
<td>3.3</td>
<td>29.1</td>
<td>1.7</td>
</tr>
</tbody>
</table>

1: 9.4 mm, 2: 5.15 mm, A: 1.48 kg/h, B: 1.97 kg/h
Product Gas Composition Variation

(continuous line CAFB-2-A, dashed line CAFB-1-A)
Product Gas Heating Value at $x^* = 1.0$

HHV (dry basis, MJ/kg)

1: 9.4 mm, 2: 5.15 mm, A: 1.48 kg/h, B: 1.97 kg/h
Average Stoichiometric Ratio (daf)

1: 9.4 mm, 2: 5.15 mm, A: 1.48 kg/h, B: 1.97 kg/h
The particle size effect and airflow effect on the gasification characteristics of coal and biomass blended fuels were experimentally investigated.

A simplified phenomenological analysis yields a linear correlation for correlating the average oxidation-front propagation velocity with the fuel properties and the airflow rate.

The results show that fuel-ash plays an important role in determining the rate of oxidation-front propagation in the fuel-bed. However, a correlation that also takes the fuel particle size in addition to the fuel properties and airflow rate into account is more appropriate and needs to be developed.

Empirical self-similar temperature profiles developed for the investigated fuels can be used to track the combustion, gasification (pyrolysis), and preheat regions as a function of time.

The molar composition of the product gas did not show much sensitivity to airflow rate and fuel particle size.
The molar composition of the product gas (dry basis) for the coal, CAFB, and CLB fuels at the top of the fuel-bed consists of 27 - 30% CO, 7 - 10% H2, 1 - 3% CH4, and 2 - 6% CO2 (remaining N2).

The product gas heating value was almost uniform for all the fuels; it ranged in-between of 4.5 - 5.12 MJ/kg and could be attributed to almost uniform exit product gas compositions.

The fundamental results show that it is feasible to co-gasify animal waste-based fuels (high-ash, low-energy content) like feedlot biomass (FB) and chicken litter biomass (LB) with (low-ash, high-energy content) coal.

This might not only reduce their disposal problems, but also reduce emission of greenhouse gases, as these are CO2 neutral fuels.
Oxidation-Front Propagation Velocity in the Fuel-Bed

If volumetric burning then:
\[
\delta_{ash,new} \approx \delta_{char,old} \\
v_{pk,prop} \approx \frac{\delta_{char}}{t_{b,char}}
\]

However, as char burns:
\[
\delta_{ash,new} < \delta_{char,old} \\
\delta_{ash,new} = \frac{\delta_{char} \rho_{char} Y_{ash,char}}{\rho_{ash}} \\
\delta_{ash,new} = \frac{Y_{O2} \rho_{air} \frac{v_{air}}{v_{O2}} \rho_{char} Y_{ash,char}}{v_{O2} n'' \dot{m}_{c,ave} \rho_{ash}}
\]
Thank You