THE EFFECT OF ATTRITION ON BIOMASS CONVERSION DURING FLUIDIZED BED COMBUSTION AND GASIFICATION

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Attrition in fluidized beds is a complex phenomenon which results from the interplay of different elementary mechanical, chemical and thermal processes and leads to different possible modes of particle breakage.
FUEL ATTRITION IN FLUIDIZED BEDS

Chirone, Massimilla and Salatino,
LIKELIHOOD AND EXTENT OF ATTRITION PHENOMENA IN THE VARIOUS COMBUSTOR SECTIONS

<table>
<thead>
<tr>
<th>Attrition location</th>
<th>Attrition mechanism</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PF</td>
</tr>
<tr>
<td>DE</td>
<td>L</td>
</tr>
<tr>
<td>DJ</td>
<td>U</td>
</tr>
<tr>
<td>DR</td>
<td>U</td>
</tr>
<tr>
<td>CY</td>
<td>U</td>
</tr>
<tr>
<td>ST</td>
<td>U</td>
</tr>
<tr>
<td>FD</td>
<td>U</td>
</tr>
</tbody>
</table>

L: likely; U: unlikely; TBA: to be assessed.
PF: primary fragmentation; SA: attrition by surface wear;
IF: fragmentation by impact loading.
• Primary fragmentation:
  • breakage of particles induced by internal mechanical stresses associated with thermal shock and/or release of volatile matter;
  • Influenced by particle size, heating rate, peak temperature, fuel texture (e.g. porosity), volatile matter content, ….
Frammentazione primaria

Heated Grid

antracite tedesca 0.95-1.2 mm

particelle trattate a temperatura differente
FUEL ATTRITION MECHANISMS

- **Fragmentation by loss of particle connectivity:**
  - Fragmentation of particles associated with enlargement and overlapping of pores and cavities followed by loss of particle connectivity (percolative fragmentation);
  - Influenced by particle texture and gasification regime.
Miccio, F., Salatino, P. and Tina, W., XXVIII Symposium on Combustion, 2000

M=1.0  conv. degree 0.0  M=0.01
Miccio, F., Salatino, P. and Tina, W., XXVIII Symposium on Combustion, 2000

M=1.0  conv. degree 0.1  M=0.01
Miccio, F., Salatino, P. and Tina, W., XXVIII Symposium on Combustion, 2000

M = 1.0, conv. degree 0.2, M = 0.01
Miccio, F., Salatino, P. and Tina, W., XXVIII Symposium on Combustion, 2000
Miccio, F., Salatino, P. and Tina, W., XXVIII Symposium on Combustion, 2000

$M=1.0$  \hspace{1cm} \text{conv. degree} 0.4  \hspace{1cm} M=0.01$
Miccio, F., Salatino, P. and Tina, W., XXVIII Symposium on Combustion, 2000
Miccio, F., Salatino, P. and Tina, W., XXVIII Symposium on Combustion, 2000

M=1.0  conv. degree 0.6  M=0.01
Miccio, F., Salatino, P. and Tina, W., XXVIII Symposium on Combustion, 2000

\[ M = 1.0 \quad \text{conv. degree} \quad 0.7 \quad M = 0.01 \]
Miccio, F., Salatino, P. and Tina, W., XXVIII Symposium on Combustion, 2000

M=1.0  conv. degree 0.8  M=0.01
Miccio, F., Salatino, P. and Tina, W., XXVIII Symposium on Combustion, 2000
Fragmentation by the action of external forces:

- Surface wear (abrasive attrition);
- Impact loading (e.g., in jets);

Both enhanced by the progress of reaction (Reaction-assisted-attrition !)
raw fuel
char: combustion
char:combustion+attrition

“coarse” char

“fine” char
Fragmentation/attrition dramatically affects fuel/char PSD, and in turn:

- Residence time of the fuel particles in the reactor;
- Heat and mass transfer;
- Intraparticle diffusion and heat transfer;
- Time-temperature history;
- Fuel burnoff (change of relevant combustion/gasification regime);
- Fate of ash (melting/vaporization).
“Intrinsic” combustion reactivity of various solid fuels
FUEL COMBUSTION/ATTRITION PATTERNS

- **RAW FUEL**
  - Pyrolysis/ Primary fragmentation
  - Combustion-assisted-attrition/ Percolative fragmentation

- **“COARSE” CHAR**
  - FCP

- **“FINE” CHAR**
  - FCF
  - FFP

- COMBUSTION PRODUCTS
  - UNBURNED CARBON
1) gas preheating section; 2) electrical furnaces; 3) ceramic insulator; 4) gas distributor; 5) thermocouple; 6) fluidization column; 7) steel basket; 8) manometer; 9) digital mass flowmeters; 10) air dehumidifier (silica gel).

1) gas preheating section; 2) electrical furnaces; 3) ceramic insulator; 4) gas distributor; 5) thermocouple; 6) fluidization column; 7) head with three-way valve; 8) sintered brass filters; 9) hopper; 10) SO$_2$ scrubber; 11) stack; 12) cellulose filter; 13) membrane pump; 14) gas analyzers; 15) personal computer; 16) manometer; 17) digital mass flowmeters; 18) air dehumidifier (silica gel).

1) gas preheating section; 2) electrical furnaces; 3) ceramic insulator; 4) gas distributor; 5) thermocouple; 6) fluidization column; 7) gas suction probe; 8) stack; 9) cellulose filter; 10) membrane pump; 11) gas analyzers; 12) personal computer; 13) manometer; 14) digital mass flowmeters; 15) air dehumidifier (silica gel).
Particle size evolution and fragmentation during combustion

No fragmentation, but agglomeration!
CHAR CONVERSION PATTERN

Pelletized straw

![Shrinking core pattern ?](image1)

Pelletized wood

![Shrinking particle pattern !](image2)
Low-reactivity carbons: afterburning of attrited fines is limited → the extent of attrition can be directly assessed by looking at unburned carbon at the exhaust;

High-reactivity carbons: burnout of attrited carbon fines is extensive over their residence time in the combustor → attrition cannot be directly assessed from unburned carbon at the exhaust. Other methods have to be envisaged.
Assessment of carbon attrition rate from carbon elutriation rate

\[ E_{c,o} = E_{c,i} \cdot \beta \cdot (1 - \xi) \]

- \( \beta \): attrition enhancement factor
- \( \xi \): degree of attrited fines afterburning
Char attrition of biomass fuels

Pelletized straw

Pelletized wood
Loss of particle connectivity

Breakage by mechanical stress

- Biomass
- Medium rank coals
- High rank coals
Fluidized bed (FB) gasification is acknowledged to have great flexibility in conversion of several solid fuels, including low rank coals, into synthesis gas.

Fuel attrition and fragmentation phenomena are well known to affect the reliability and efficiency of FB combustion and gasification processes.

Attrition/fragmentation cause the elutriation of fine material from the bed that results in the loss of unconverted carbon.

Attrition/fragmentation may also significantly change the particle size distribution of the materials in the bed which influences the bed fluid-dynamics, heat and mass transfer coefficients and reaction rates.
Secondary fragmentation during gasification (lignite)

$T = 850 \, ^\circ\text{C}$, $U = 0.4 \, \text{m/s}$, Gas = 100% CO$_2$

$t_0 = 0\, \text{min}$
$X_{C0} = 0\%$

$t_1 = 30\, \text{min}$
$X_{C1} = 35.9\%$

$t_2 = 50\, \text{min}$
$X_{C2} = 56.3\%$

$t_3 = 70\, \text{min}$
$X_{C3} = 71.2\%$

$t_4 = 90\, \text{min}$
$X_{C4} = 81.0\%$

$t_5 = 110\, \text{min}$
$X_{C5} = 86.2\%$

t = \text{gasification time, } X_C = \text{carbon conversion degree}
Char attrition during gasification – temperature effect

Elutriation rate

Carbon conversion

Operating Temperature | Gasification time (min) | Gasified carbon (%) | Elutriated carbon (%) | Unconverted carbon (%)
--- | --- | --- | --- | ---
T = 800°C | 480 | 86.4 | 8.9 | 4.7
T = 850°C | 240 | 91.4 | 4.8 | 3.8
T = 900°C | 160 | 96.2 | 3.4 | 0.4

U = 0.4 m/s
W<sub>b</sub>atch = 1 g
Gas = 100% CO<sub>2</sub>

lignite
Char attrition during gasification – gas concentration effect

**Elutriation rate**

<table>
<thead>
<tr>
<th>CO₂ inlet concentration (in N₂)</th>
<th>Gasification time (min)</th>
<th>Gasified carbon (%)</th>
<th>Elutriated carbon (%)</th>
<th>Unconverted carbon (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20%</td>
<td>300</td>
<td>85.4</td>
<td>10.0</td>
<td>4.6</td>
</tr>
<tr>
<td>50%</td>
<td>200</td>
<td>91.8</td>
<td>5.2</td>
<td>3.0</td>
</tr>
<tr>
<td>100%</td>
<td>160</td>
<td>96.2</td>
<td>3.4</td>
<td>0.4</td>
</tr>
</tbody>
</table>

**Carbon conversion**

\[ T = 900°C \]
\[ U = 0.4 \text{ m/s} \]
\[ W_{\text{batch}} = 1 \text{ g} \]
\[ \text{Gas} = 20-100\% \text{ CO}_2 \text{ in N}_2 \]
The effect of pre-treatment

- Biomass fuels are characterized by a low energy specific content if compared with fossil fuels.
- One option is fuel pre-treatment (pelletization, torrefaction, compaction), to increase bulk density and specific energy content, and improve fuel properties.
- Biomass, characterized by highly reactive chars, can also be suitably used in processes where the fuel gasification is carried out at relatively low temperature (chemical looping combustion and sorption enhanced gasification).
## Fuel materials

<table>
<thead>
<tr>
<th></th>
<th>Wood chips</th>
<th>Wood pellets</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHV, kJ/kg</td>
<td>11700</td>
<td>18500</td>
</tr>
<tr>
<td>Proximate analysis</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(as received), %&lt;sub&gt;W&lt;/sub&gt;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>moisture</td>
<td>34.9</td>
<td>8.4</td>
</tr>
<tr>
<td>volatiles</td>
<td>51.6</td>
<td>74.2</td>
</tr>
<tr>
<td>fixed carbon</td>
<td>13.3</td>
<td>17.1</td>
</tr>
<tr>
<td>ash</td>
<td>0.2</td>
<td>0.3</td>
</tr>
<tr>
<td>Ultimate analysis</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(dafb), %&lt;sub&gt;W&lt;/sub&gt;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>carbon</td>
<td>47.5</td>
<td>49.4</td>
</tr>
<tr>
<td>hydrogen</td>
<td>6.1</td>
<td>5.9</td>
</tr>
<tr>
<td>nitrogen</td>
<td>0.2</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>oxygen (diff)</td>
<td>46.2</td>
<td>44.6</td>
</tr>
</tbody>
</table>

Pellet size = 6x20mm

Chip size = 6.35-9mm
Primary fragmentation tests results

- **Temperature**: $T = 800 \, ^\circ C$
- **Velocity**: $U = 0.3 \, m/s$
- **Gas**: $N_2$
- **Time**: 5 min

<table>
<thead>
<tr>
<th></th>
<th>$d_0$, mm</th>
<th>$S_f$</th>
<th>$n_1$</th>
<th>$d_1$, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood chips</td>
<td>10.4</td>
<td>0.95</td>
<td>4.5</td>
<td>5.3</td>
</tr>
<tr>
<td>Wood pellets</td>
<td>6.0</td>
<td>0.29</td>
<td>1.4</td>
<td>4.9</td>
</tr>
</tbody>
</table>

- $d_0$: initial Sauter diameter
- $S_f$: primary fragmentation probability
- $n_1$: primary fragmentation multiplication factor
- $d_1$: final Sauter diameter

**Particle shrinkage!**
Char attrition tests results – attrition rate

\[ T = 800 \, ^\circ\text{C} \]
\[ U = 0.8 \, \text{m/s} \]
\[ W_{\text{batch}} = 2 \, \text{g} \]
\[ \text{Gas} = N_2 \, (\text{inert}) \]
\[ = N_2 + O_2 \, (4.5\%) \, \text{(combustion)} \]
\[ = N_2 + CO_2 \, (60\%) \, \text{(gasification)} \]

<table>
<thead>
<tr>
<th>Material</th>
<th>inert</th>
<th>combustion</th>
<th>gasification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood chips</td>
<td>23</td>
<td>2.65</td>
<td>48</td>
</tr>
<tr>
<td>Wood pellets</td>
<td>6</td>
<td>0.35</td>
<td>26</td>
</tr>
</tbody>
</table>

Percentage of the initial carbon cumulatively elutriated

Combustion- and gasification-assisted mechanism
Char attrition tests results – carbon conversion

52%  
74%

Pelletized biomass showed a higher carbon conversion!

T = 800 °C  
U = 0.8 m/s  
W_{batch} = 2 g  
Gas = N_2 + O_2 (4.5%)  
(combustion)  
= N_2 + CO_2 (60%)  
(gasification)
Extensive primary fragmentation is experienced by biomass fuels (e.g. wood chips) upon devolatilization, significantly influencing average PSD of the fuel.

Particle breakage by primary fragmentation is limited for pelletized biomass, indicating that pelletization procedure is able to give mechanical strength to the particles.

Attrition of carbon fines during char combustion is limited for biomass because of extensive fines afterburning.

Attrition of carbon fines from the char particles during gasification is extensive for biomass. Pelletization is able to decrease the extent of fines generation by attrition.

A gasification-assisted attrition mechanism is proposed to explain the experimental results. The low reactivity of the generated fines under gasification conditions makes the loss of carbon by fines elutriation much more significant than that found under combustion conditions.