ATTRITION OF LIGNITE CHAR DURING FLUIDIZED BED GASIFICATION: EXPERIMENTAL AND MODELING STUDIES

Paola Ammendola and Fabrizio Scala
Introduction

✓ The urgent need to capture and sequester CO₂ in particular emitted from the use of coal has triggered the development of new processes like chemical looping combustion and sorption enhanced gasification.

✓ Both these processes require that fuel gasification is carried out at a relatively low temperature, limiting the types of fuel that could be used to those with highly reactive chars, such as low-rank coals and biomass.

✓ Lignite is an abundant fuel and makes up approximately 40% of coal reserves in the world. Its commercial use is forecast to grow substantially.

✓ However, lignite usually has high water and oxygen content, low energy density, and it is expensive to transport. All these characteristics have limited its utilization.
Introduction

- 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.
- Several attrition studies are reported under FB combustion conditions, but only limited activity is reported under gasification conditions, and no study could be found in the literature on attrition of lignite during gasification.
Introduction

The authors started a study on attrition of lignite char, pointing out that fragmentation and attrition of the char particles during gasification were significant, and suggested a *gasification-assisted attrition* enhancement effect.

This mechanism, associated to the low reactivity of the generated fines, made the loss of carbon by fines elutriation during char gasification more significant than that typically found under combustion conditions.

t = gasification time, $X_C$ = carbon conversion degree

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

- In this work the attrition behaviour of char from an Italian lignite (Sulcis) was studied under CO₂ gasification conditions in a lab-scale FB apparatus.
- In particular, attrition was characterized as a function of the char conversion degree.
- The influence of bed temperature and CO₂ concentration on attrition and carbon conversion was investigated.
- On the basis of the experimental results, a kinetic model of lignite char under CO₂ gasification conditions was developed in order to predict the time resolved profiles of carbon conversion.
- The mechanical resistance of the char particles was also characterized at different stages of char conversion by specific attrition experiments.
- A semi-empirical model was finally developed to simulate the experimental profiles of carbon elutriation rate as a function of time.
Experimental

Sulcis lignite properties

Proximate analysis, % (as received)

<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture</td>
<td>6.3</td>
</tr>
<tr>
<td>Ash</td>
<td>16.9</td>
</tr>
<tr>
<td>Volatile Matter</td>
<td>49.7</td>
</tr>
<tr>
<td>Fixed Carbon</td>
<td>27.1</td>
</tr>
</tbody>
</table>

Ultimate analysis, % (dry and ash free basis)

<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>71.7</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>5.7</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>1.8</td>
</tr>
<tr>
<td>Oxygen</td>
<td>13.1</td>
</tr>
<tr>
<td>Sulphur</td>
<td>7.7</td>
</tr>
</tbody>
</table>

LHV, kcal/kg 5137

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Char attrition tests results – temperature effect

Elutriation rate

Carbon conversion

<table>
<thead>
<tr>
<th>Operating Temperature</th>
<th>Gasification time (min)</th>
<th>Gasified carbon (%)</th>
<th>Elutriated carbon (%)</th>
<th>Unconverted carbon (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T = 800°C</td>
<td>480</td>
<td>86.4</td>
<td>8.9</td>
<td>4.7</td>
</tr>
<tr>
<td>T = 850°C</td>
<td>240</td>
<td>91.4</td>
<td>4.8</td>
<td>3.8</td>
</tr>
<tr>
<td>T = 900°C</td>
<td>160</td>
<td>96.2</td>
<td>3.4</td>
<td>0.4</td>
</tr>
</tbody>
</table>

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Char attrition tests results – CO$_2$ effect

**Elutriation rate**

- **A**
  - T = 900°C
  - U = 0.4 m/s
  - W$_{\text{batch}}$ = 1 g
  - Gas = 20-100% CO$_2$ in N$_2$

**Carbon conversion**

- **B**

**Table: Gasification results**

<table>
<thead>
<tr>
<th>CO$_2$ inlet concentration (in N$_2$)</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>

Attrition of lignite char during fluidized bed gasification: experimental and modeling studies

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Char gasification in the present operating conditions is controlled by intrinsic kinetics.

The concentration of produced CO is negligible (<1% of CO₂ concentration).

\[
\frac{dX_C}{dt} = A(X_C) \cdot k_0 \cdot \exp\left(-\frac{E_a}{RT}\right) \cdot \left[\frac{C_{CO_2}}{C_{CO_2} + \beta}\right] \\
A(X_C) = a + b \cdot X_C + c \cdot X_C^2
\]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>0.964</td>
</tr>
<tr>
<td>b</td>
<td>0.460</td>
</tr>
<tr>
<td>c</td>
<td>1.42</td>
</tr>
<tr>
<td>(k_0)</td>
<td>1.53 \times 10^5</td>
</tr>
<tr>
<td>(E_a/R)</td>
<td>22300</td>
</tr>
<tr>
<td>(\beta)</td>
<td>0.625</td>
</tr>
</tbody>
</table>

U = 0.4 m/s, Gas = 100% CO₂

T = 900 °C, U = 0.4 m/s
Kinetic model - results

U = 0.4 m/s, Gas = 100% CO₂

T = 900 °C, U = 0.4 m/s
In order to understand the relationship between the char attrition constant \( k \) and carbon conversion \( X_C \), attrition experiments were carried out under inert conditions (100% \( \text{N}_2 \)) using char samples pre-gasified for different times (ranging from 10 to 50 min).

Pre-conversion of the char significantly enhances the mechanical attrition of the particles.

\[ E_C = k \cdot (U - U_{mf}) \cdot (W_C / d) \]

Attribute rate

\[ W_C = W_{C0} \cdot (1 - X_C) \]

Carbon mass

\[ k = 1.5 \cdot 10^{-6} \cdot \exp(2.31 \cdot X_C) \]
✓ Only limited secondary fragmentation occurs at low carbon conversions, while significant shattering is evident at conversions larger that 50%.

**Char particle size**

\[
d(X_C) = d_0 \cdot \sqrt[3]{1/n(X_C)}
\]

**Number of char particles**

\[
n(X_C) = 1 + (n_{max} - 1) \cdot \left[ \frac{(X_C - X_C^*)}{(1 - X_C^*)} \right]
\]

\[
X_C^* = 0.5
\]

\[
n_{max} = \text{fitting parameter}
\]

Comparison between experimental and model time resolved carbon elutriation rates obtained during CO₂ gasification experiments at different operating conditions.
A gasification-assisted attrition mechanism is proposed. Internal reaction progressively weakens the structure inside the particle, enhancing particle attrition.

The low reactivity of the generated fines under gasification conditions makes the loss of carbon by fines elutriation significant.

The total elutriated carbon increased when the bed temperature is decreased. Two reasons are likely to determine this behaviour: i) at lower temperatures the residence time for complete gasification increases; ii) the extent of in-bed conversion of the attrited fines increases with the bed temperature.

The total elutriated carbon increased when the CO₂ concentration was decreased. At lower CO₂ concentrations the residence time of particles in the bed increases and the extent of in-bed conversion of the attrited fines decreases.

On the whole, the carbon loss by elutriation is certainly one of the critical factors during the gasification process, especially at low gasification rates (i.e. at low CO₂ concentration and bed temperature).
Conclusions - 2

- A char gasification kinetic model was proposed which was able to correctly predict the carbon conversion as a function of time found in the experiments, including the effect of temperature and CO\textsubscript{2} concentration on carbon conversion.
- A semi-empirical carbon elutriation model was also presented, where the char attrition constant was expressed as a function of the carbon conversion degree.
- The change of the average char particle size due to secondary fragmentation was taken into account.
- Model results were in good agreement with the curves obtained from the experimental tests.
- Particle fragmentation appears to be a key phenomenon in determining the attrition rate of the char in the bed.
- Nevertheless, the presence of a fitting parameter, i.e., the maximum number of generated fragments, implies that the model is not yet predictive at this stage.