Self-steam explosion pretreatment technology for milling application of wet biomass

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I H I Corporation
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3. Comparison with mechanical mills
4. Summary
1. Background
Japan Ambitious Target

JAPAN CLIMATE CHANGE

Japan aims to slash greenhouse gas emissions by 26 percent by 2030

EFE | Tokyo | 17 Jul 2015

Japan’s electricity generation 2015*

Reduction of CO\textsubscript{2} emission from coal-fired power plant and the widespread of renewable energy, particularly biomass, are indispensable

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*IEA Energy Balance of OECD Countries (2017 edition)
Replacement part of coal by carbon neutral resources such as biomass, namely co-firing technology, is expected to be a visible way to reduce CO$_2$ emission from coal-fired power plant.

### Direct Co-firing
- Simple
- Low Investment Cost

### Indirect Co-firing

### Parallel Co-firing

<table>
<thead>
<tr>
<th></th>
<th>Coal Firing</th>
<th>Co-firing</th>
<th>Biomass Firing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of boiler</td>
<td>PC</td>
<td>PC</td>
<td>CFB</td>
</tr>
<tr>
<td>Thermal Efficiency</td>
<td>40-45%</td>
<td>40-45%</td>
<td>30%</td>
</tr>
<tr>
<td>Investment Cost</td>
<td>-</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Risks of ash-related problems</td>
<td>Low</td>
<td>Moderate</td>
<td>High</td>
</tr>
<tr>
<td>CO$_2$ emission</td>
<td>High</td>
<td>Low</td>
<td>-</td>
</tr>
<tr>
<td>SO$_x$, NO$_x$ emission</td>
<td>High</td>
<td>Moderate</td>
<td>Low</td>
</tr>
<tr>
<td>Fuel Flexibility</td>
<td>Low</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Fuel size</td>
<td>&lt; 1 mm</td>
<td>&lt; 1 mm</td>
<td>&lt; 13 mm</td>
</tr>
</tbody>
</table>

Type of co-firing technology
Problems with Biomass Fuel

- High Moisture Content
  Moisture content of biomass: 40 – 70%

- Poor Grindability
  Due to its fibrous structure, biomass is generally hard to be milled/grounded.

Vibration mill  Knife mill  Hammer mill  Roller mill

Conventional mechanical mills
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- High Hygroscopic
  Easy to absorb water

Thermal efficiency of coal-fired power plant: 40%

It requires 30-76% the HHV of biomass for milling step (< 1-2 mm)

Instead of using electricity, the use of thermal energy for biomass milling is preferable
Problems with Biomass Fuel

❖ Pretreatment Technology

Steam Explosion: Steam treatment + spontaneously depressurization

Steam/water adiabatically expanded and crushed biomass into small particles

Steam Explosion has not been explored yet for milling application
First, we investigated the effect of steam explosion conditions on biomass size reduction.
Conv. SE – Experimental Method

**Biomass Steam Explosion**

**Sieving (1st Separation)**
- Above 1 mm
- Below 1 mm

**Drying**

**Milling**

**Sieving (2nd Separation)**
- Above 1 mm
- Below 1 mm

**Ball mill (Low rpm)**

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**Index to represent treatment severity** (severity factor, $R_0$)

$$ R_0 = \log_{10} \int_{0}^{t} \exp \left( \frac{T(t) - 100}{14.75} \right) dt $$

**Short heating time (Conv. SE)**

$$ R_0 = t \times \exp \left( \frac{T - 100}{14.75} \right) $$

**Longer heating time (Self-SE)**

$$ R_0 = \log_{10} \sum \frac{14.75(t_{n+1} - t_n)}{(T_{n+1} - T_n)} \left[ \exp \left( \frac{T_{n+1} - 100}{14.75} \right) - \exp \left( \frac{T_n - 100}{14.75} \right) \right] $$

$T$ : Temperature (°C)
$t$ : holding time

*Priyanto et al., Advanced Powder Technol. 28 (7) (2017), pp. 1660-1667*
Effect of temperature/pressure

However, lack of significant effect at \( P > 2.8 \) MPa on the size reduction due to the condensation of large amount of steam

Optimum condition
Severity at 5.2-5.4
SE consumes less energy than mechanical mill (cutter mill).

However,

- Moisture content of fine solid products after SE was high (60-70%), requiring the addition of post-drying process.
- Steam can't be recycled without water treatment.
Why don’t use the moisture from biomass as steam feedstock and indirectly heat-up biomass (high recyclability) ?

Self-Steam Explosion$^+$
✓ No need of pre-drying step
✓ Minimize condensation of produced steam → Lower MC of solid products
✓ Minimize waste water treatment

Priyanto et al., ACS Sustainable Chemistry & Engineering 6(3) (2018), pp. 2905-2910
Self-SE – Experimental Method

Soaking in tap water (1 day)

MC Adjustment
MC : 45-60%

Temperature & Pressure Profile during treatment
The increase of T accelerates the degradation of biomass component by formed steam, weakening the strength structure of plant cell wall.

The pressure release causes adiabatic expand of steam/water inside cell wall (explosive effect), reducing the size of biomass into fine particles.
Size-reducibility by self-SE method

EFB > Sakura > Cedar
Hardwood    Softwood

However, **regardless the type of biomass, Self-SE method effectively reduced the size of biomass chips into fine particles**
Effect of biomass chips

Self-SE method effectively reduced the size of coarse chips (< 22 mm) into fine particles.
To confirm the ability of this proposed self-SE method to reduce the biomass particle size and upgrade the biomass properties

Direct reduction in the biomass particle size can be achieved by applying the SE method to the raw material. The self-SE method can also significantly improve the properties of the raw material. This is because the self-SE method can increase the degree of polymerization and the degree of condensation in the biomass, which in turn reduces the biomass particle size and improves its properties. The self-SE method can also be used to upgrade the biomass properties by increasing the HHV, volatile matter, and fixed carbon content of the biomass.

<table>
<thead>
<tr>
<th>Analysis Items</th>
<th>Sakura</th>
<th>Cedar</th>
<th>EFB</th>
</tr>
</thead>
<tbody>
<tr>
<td>HHV (MJ/kg)</td>
<td>19.2</td>
<td>19.6</td>
<td>17.1</td>
</tr>
</tbody>
</table>

**Proximate analysis (wt%-db)**

<table>
<thead>
<tr>
<th>Analysis Items</th>
<th>Sakura</th>
<th>Cedar</th>
<th>EFB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volatile matter</td>
<td>84.6</td>
<td>80.5</td>
<td>76.0</td>
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<tr>
<td>Fixed carbon</td>
<td>15</td>
<td>13.8</td>
<td>19.4</td>
</tr>
<tr>
<td>Ash content</td>
<td>0.4</td>
<td>0.4</td>
<td>4.6</td>
</tr>
</tbody>
</table>

**Ultimate Analysis (wt%-daf)**

<table>
<thead>
<tr>
<th>Analysis Items</th>
<th>Sakura</th>
<th>Cedar</th>
<th>EFB</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>49.8</td>
<td>51.7</td>
<td>50.0</td>
</tr>
<tr>
<td>H</td>
<td>6.4</td>
<td>6.0</td>
<td>6.0</td>
</tr>
<tr>
<td>S</td>
<td>0.01</td>
<td>0.02</td>
<td>0.09</td>
</tr>
<tr>
<td>N</td>
<td>0.11</td>
<td>0.01</td>
<td>0.38</td>
</tr>
<tr>
<td>O (diff)</td>
<td>43.7</td>
<td>42.3</td>
<td>43.5</td>
</tr>
</tbody>
</table>

**Ash components (wt%-ash, free Fe)**

<table>
<thead>
<tr>
<th>Analysis Items</th>
<th>Sakura</th>
<th>Cedar</th>
<th>EFB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Na₂O</td>
<td>1.7</td>
<td>0.8</td>
<td>0.5</td>
</tr>
<tr>
<td>MgO</td>
<td>8.0</td>
<td>2.8</td>
<td>3.9</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>0.3</td>
<td>0.2</td>
<td>1.3</td>
</tr>
<tr>
<td>SiO₂</td>
<td>0.4</td>
<td>0.6</td>
<td>16.2</td>
</tr>
<tr>
<td>P₂O₅</td>
<td>3.0</td>
<td>2.2</td>
<td>3.2</td>
</tr>
<tr>
<td>SO₃</td>
<td>1.1</td>
<td>2.1</td>
<td>4.2</td>
</tr>
<tr>
<td>K₂O</td>
<td>33.2</td>
<td>26.5</td>
<td>57.4</td>
</tr>
<tr>
<td>CaO</td>
<td>50.2</td>
<td>64.4</td>
<td>6.7</td>
</tr>
<tr>
<td>MnO</td>
<td>2.0</td>
<td>0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>TiO₂</td>
<td>0.0</td>
<td>0.0</td>
<td>0.1</td>
</tr>
<tr>
<td>Cl</td>
<td>-</td>
<td>-</td>
<td>6.3</td>
</tr>
</tbody>
</table>

Self-SE Sakura (220 °C) | Self-SE Cedar (220 °C) | Self-SE EFB (210 °C) | Self-SE EFB + Water leaching

| HHV (MJ/kg) | 23.5 | 23.6 | 19.6 | 21.1 |
| Volatile matter | 70.8 | 72.0 | 67.4 | 71.4 |
| Fixed carbon | 28.9 | 27.2 | 24.2 | 26.5 |
| Ash content | 0.3  | 0.8  | 8.4  | 1.6  |

By adding simple treatment (water leaching, i.e. 20 °C for 30 min) for self-SE EFB, the ash, alkali and chlorine content can be reduced dramatically → reduce ash-related problems when combusted

**Preferable as fuel for PC Boiler**
3. Comparison with mechanical mills
Advantages of Self-SE method

✓ **Produce Finer Particles**

![Image of finer particles produced by self-SE method]

✓ **Higher Quality of Solid Products**

- Higher HHV (20%)
- Higher hydrophobicity

![Image of higher quality solid products]

✓ **Low Energy Consumption**

![Energy consumption comparison between self-SE and Cutter mill]

**Self-SE method** cut half of total energy required by conventional method
4. Summary
✓ We introduced a novel method, namely self-SE, to mill and upgrade biomass
✓ Self-SE process was particularly effective in producing fine particles (average particle size <1 mm) from biomass samples measuring 5–22 mm
✓ Fine particles produced by this technique exhibited smaller particle sizes, higher heating values, and greater hydrophobicity than those produced by the conventional cutter milling process.
✓ The self-SE technique also reduced energy consumption by more than half compared to cutter milling.

Next Challenges

• Shortening the heating time
• Scaling up (FS Study) → funded by Ministry of Environment, Japan
the Forestry and Forest Product Research Institute of Japan (FFPRI) for providing the conventional SE apparatus were greatly acknowledged.