Fuel moisture soft-sensor and its validation for the industrial BioGrate boiler

Jukka Kortela, Sirkka-Liisa Jämsä-Jounela
Aalto University School of Chemical Technology
NPCW 2012
Contents

• Objectives
• Description of the Biograte process
• Fuel moisture soft-sensor
• Description of the testing environment
• The test results of the fuel moisture soft-sensor
• Conclusions
Objectives of the advanced control of the plant

• The main objective is to control the plant and avoid shutdowns while burning wide variety of problematic biofuels with fluctuating fuel quality and moisture

• To keep constant power production with fluctuating fuel quality and moisture

• To react sudden changes of power demand
  – with fluctuating fuel quality and moisture
  – with long time delays
Objectives of the fuel moisture soft-sensor

- The fuel moisture soft-sensor is needed to achieve control objectives
  - Robust control is not efficient because fuel moisture is not measured and process dynamics contain long delays
  - Estimating fuel moisture allows control to compensate the affect of moisture variation
Description of the Biograte process

• The fuel is fed onto the center of a grate from below by a stoker screw.
• Alternate rotating rings are pushed clockwise or counterclockwise respectively.
Description of the Biograte process

Flow chart of BioPower HW application

- Make-up water
- Feed water
- Hot water
- Steam
- Air
- Flue gas
- Ash
- Fuel

*= option

Main Performance Data

Aalto University
School of Chemical Technology
Description of the delays in the Biograte process

- The BioGrate process is characterized by large time constants and long dead times

<table>
<thead>
<tr>
<th>Input variable</th>
<th>Output variable</th>
<th>Step response</th>
<th>Dead time</th>
<th>Time constant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary air flow</td>
<td>Combustion power</td>
<td></td>
<td>30s</td>
<td>2s</td>
</tr>
<tr>
<td>Moisture in fuel feed</td>
<td>Combustion power</td>
<td></td>
<td>15min</td>
<td>10min</td>
</tr>
<tr>
<td>Drum pressure</td>
<td>Secondary superheater</td>
<td></td>
<td>4s</td>
<td>20min</td>
</tr>
<tr>
<td>Drum pressure</td>
<td>Fuel moisture soft-sensor</td>
<td></td>
<td>4s</td>
<td>&lt;1min</td>
</tr>
<tr>
<td>Drum pressure</td>
<td>Combustion power Estimation</td>
<td></td>
<td>4s</td>
<td>&lt;1min</td>
</tr>
</tbody>
</table>
Control of BioGrate boiler

- Hot hot water power / flow control
- Change in power demand
- Drum pressure control
- Total air / Primary air control
- Oxygen correction control
- Primary air fan
- Total air / Secondary air control
- Secondary air fan
- Stoker motor speed

Diagram:
- Boiler
- BioGrate
- Stoker speed
- Primary air
- Drum pressure
- Turbine
- Hot water network
Contents

- Objectives
- Description of the Biograte process
- Fuel moisture soft-sensor
- Description of the testing environment
- The test results of the fuel moisture soft-sensor
- Conclusions
Fuel moisture soft-sensor

• The fuel moisture disturbance $w$ is estimated with least squares

$$\min J(w) = \sum_{i=0}^{N} \left| h_2(i) - \hat{h}_2(i | w) \right|^2$$

where $h_2$ is the output enthalpy of the secondary superheater

• The fuel moisture soft-sensor is based on following sub models

  – **Superheater model** estimates the output enthalpy $h_2$ of the secondary superheater
  
  \[ \frac{dh_2}{dt} = \frac{1}{\rho V} \left( Q_t + m_1 h_1 - m_2 \hat{h}_2 \right) \text{[MJ / s]} \]

  \[ Q_t = \alpha_c m_2^{0.8} (T_w - T) \text{[MJ / s]} \]

  \[ T_w = \frac{1}{m_c C_p} (Q_w - Q_t) \text{[K / s]} \]

  \[ Q_w = \alpha_m m_{fg}^{0.65} \left( T_{fg} - T_w \right) + k_w \left( T_{fg}^4 - T_w^4 \right) \text{[MJ / s]} \]

  – **Flue gas model** estimates flue gas flow $m_{fg}$ and flue gas temperature $T_{fg}$

  – **Combustion model** estimates fuel flow $m_f(w)$
Fuel moisture soft-sensor: Flue gas

- Flue gas flow is:
  \[ \hat{m}_{fg} = \hat{m}_f(w) \cdot N_{fg} \text{ [kg/s]} \]

  and \( N_{fg} \) is flue gas flow for one kilogram of fuel (mol/kg).

- Flue gas temperature is:
  \[ \hat{T}_{fg} = \frac{q_f + 0.21 \left( \frac{F_{Air}}{22.41 \cdot 10^{-3} \cdot \hat{m}_f(w)} \right) C_{O_2} + 0.79 \left( \frac{F_{Air}}{22.41 \cdot 10^{-3} \cdot \hat{m}_f(w)} \right) C_{N_2}}{n_C C_{CO_2} + n_S C_{SO_2} + \left( n_{H_2O} + n_{H_2} \right) C_{H_2O} + \left( 3.76 \cdot N_{O_2}^{\hat{g}} + n_{N_2} \right) C_{N_2} + 0.21 \cdot N_{ExAir} C_{O_2} + 0.79 \cdot N_{ExAir} C_{N_2}} \]

  where \( q_f \) is effective heat value of wet fuel, \( F_{air} \) is total air flow (m³/s), \( C_i \) is specific heat capacity (J/molT), and \( N_{ExAir} \) is excess air (mol/kg).
Fuel moisture soft-sensor: Combustion

- The fuel flow \( m_f(w) \) is given as follows:

\[
\hat{m}_f(w) = \frac{\left(0.21 - \frac{X_{O_2}}{100}\right) n_{\text{Air}}}{N_{O_2}^g + \frac{X_{O_2}}{100} \left(N_{fg} - 4.76 \cdot N_{O_2}^g\right)} \quad [\text{kg/s}]
\]

where \( X_{O_2} \) is oxygen content of flue gas (\%),
\( n_{\text{Air}} \) is total air flow (mol/s),
\( N_{O_2}^g \) oxygen needed to burn 1 kilogram of fuel (mol/kg), and
\( N_{fg} \) is flue gas flow for one kilogram of fuel (mol/kg)
Contents

• Objectives
• Description of the Biograte process
• Fuel moisture soft-sensor
• Description of the testing environment
• The test results of the fuel moisture soft-sensor
• Conclusions
Description of the testing environment

- The experiments were conducted at the BioPower 5 CHP plant that produce 13.5 MW heat and 2.9 MW electricity.

Two fuels were used:
1. spruce bark with the moisture content of 57%
2. dry woodchips (spruce) with the moisture content of 20%

- Dry biomass was fed manually into the screw conveyor between wet fuel through the extra feeding box.
The accuracy of the fuel moisture soft-sensor was investigated by

- Sampling fuel feed every 5 minutes.
- Servomex 2500 FT-IR flue gas moisture analyzer. Samples were recorded every second.
Contents

- Objectives
- Description of the Biograte process
- Fuel moisture soft-sensor
- Description of the testing environment
- The test results of the fuel moisture soft-sensor
- Conclusions
The test results of the fuel moisture soft-sensor: Accuracy

- According to the fuel sampling, the wet fuel contained 54.4% moisture per kg fuel on average. The fuel moisture soft-sensor content resulted in an average fuel moisture content of 54.6% per kg fuel.
- Dry fuel contained 25.9% moisture per kg fuel on average. The fuel moisture soft-sensor content resulted in an average fuel moisture content of 27% per kg fuel.

![Graph showing fuel moisture soft-sensor (thick line), sampled fuel moisture (stars), and fuel moisture calculated from the FT-IR measurement (thin line) for comparison.](image-url)
The test results of the fuel moisture soft-sensor: Dynamic behaviour

- The fuel moisture soft-sensor responds to step changes within 1 minute compared with FT-IR according to the test results and cross-correlation analysis.

Fuel moisture soft-sensor (thick line), sampled fuel moisture (stars), and fuel moisture calculated from the FT-IR measurement (thin line) for comparison.

Grate temperatures during the test. The grate rings are numbered from the center (Grate ring 2) to the edge of the grate (Grate ring 12).
Conclusions

• Fuel moisture soft-sensor opens new possibilities to control combustion:
  – Fuel moisture soft-sensor shows a decrease in fuel moisture 20 minutes before drum pressure drops
  – Fuel moisture soft-sensor responds to step changes within 1 minute compared with FT-IR.
• Fuel moisture soft-sensor value and the sampled moisture content matches well
• In 15 MW BioPower CHP plant average 0.5 million euros is saved yearly