Applications of Biomass Drying and Condensing Boilers in the Process Industry


SUWIC, Department of Chemical and Process Engineering Sheffield University
Outline

- Objectives
- Biomass Drying and Case Study
- Industrial Condensing Boilers & Heat Pumps
- Case Study: Thermal Design of a Condenser in a Biomass Heating Plant
  - Heat exchanger design
  - Cost estimation
- Conclusions
Objectives

- To investigate the feasibility of exploiting low grade waste heat to dry biomass fuel for power generation
- Thermal design of a condensing boiler in a large scale district heating plant, which exploits the large amount of low grade heat available from a flue gas condensing system
# Moisture in Biomass

<table>
<thead>
<tr>
<th>Biomass Type</th>
<th>Moisture (%)</th>
<th>Bulk density (kg/m³, w.b.)</th>
<th>HHV (MJ/kg, d.b.)</th>
<th>HHV (MJ/kg, w.b.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulp &amp; paper sludge</td>
<td>50%-60%</td>
<td>500-900</td>
<td>15-19</td>
<td>6@35%</td>
</tr>
<tr>
<td>Wood Bark</td>
<td>30%-60%</td>
<td>290 - 380</td>
<td>19-25</td>
<td>11@50%</td>
</tr>
<tr>
<td>Wood Chips</td>
<td>30%-55%</td>
<td>260 - 320</td>
<td>19-21</td>
<td>10@50%</td>
</tr>
<tr>
<td>Milled Peat</td>
<td>45%-55%</td>
<td>300 - 400</td>
<td>19-21</td>
<td>10@50%</td>
</tr>
<tr>
<td>Sugarcane Bagasse</td>
<td>48%-52%</td>
<td>80 - 130</td>
<td>18.6-20.3</td>
<td>10@50%</td>
</tr>
<tr>
<td>Wood pellets</td>
<td>7%-12%</td>
<td>550 - 700</td>
<td>17-20</td>
<td>18.7@8%</td>
</tr>
</tbody>
</table>
**Biomass drying**

- Provide a value-added fuel
- Ensure a constant moisture content to optimise the combustion process
  - <30% for long-term storage and domestic applications
  - <10-30% for small-scale furnaces
  - <10-15% for the production of pellets or briquettes
- Drying is an energy-intensive process

![Pie charts showing costs and process stages](chart.png)
### Biomass Drying – Commercial Dryers

**Medium:**
- Air
- Flue gas
- Steam

#### Rotary dryer
- Variable particle sizes
- Reasonable dimension
- Robust

#### Belt dryer
- Variable particle sizes
- Robust
- Low temperature drying

#### Flash dryer
- Steam – heat recycle
- Reasonable dimension
- Uniform & low temperature
- High M/H transfer

#### Fluidized bed
- Steam – heat recycle
- Small particle
- Abrasion among particles
- Leakage in steam dryer

#### Advantages
- Variable particle sizes
- Robust
- Small & uniform particle

#### Disadvantages
- Corrosion and erosion
- Blocked by long bark
- Fire risk after drying
- Larger dimension of dryer
- High hazard risk
Low grade thermal energy recovery by drying biomass – Case study

40% flue gas
250 °C - 450 °C;
647 - 336 t/h

60% hot water
90 °C; 737 t/h

Heating Sources

100 MW

40 MW

Biomass

Drying
Case study – Drying load

- Wood chips required for the 40MW power plant

\[
M_{\text{wood}} (\text{kg/s}) = \frac{\text{power input in power plant} \times 40 (\text{MW})}{\text{fuel heating value} (\text{MJ/kg – d.b.)}}
\]

- Drying load for the drying process

\[
W(\text{kg/s}) = M_{\text{wood}} \times (\text{MC}_{\text{in}} - \text{MC}_{\text{out}})
\]

<table>
<thead>
<tr>
<th>Moisture change (wt%-%wet)</th>
<th>(kg/s)</th>
<th>(t/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>initial, final</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.6, 0.1</td>
<td>3.33</td>
<td>12.00</td>
</tr>
<tr>
<td>0.6, 0.2</td>
<td>3.00</td>
<td>10.80</td>
</tr>
<tr>
<td>0.6, 0.3</td>
<td>2.57</td>
<td>9.26</td>
</tr>
</tbody>
</table>
Case study – Belt dryer

A Continuous Cross-Flow Belt Dryer
Case study: mass and heat balances

- Biomass drying by flue gas

- Biomass drying by superheated steam
Case study – Heat input requirement

Drying by flue gas

Drying by steam

Drying by steam

Drying by steam
Case study – Size estimation

Belt Cross-sectional area:

\[ A_{\text{eff}} = \frac{M_{\text{wood}} (1 + MC) \times \tau_{\text{wood}}}{W_{\text{load}}} \]

- \( M_{\text{wood}} \): solid mass flow rates
- \( MC \): moisture content
- \( W_{\text{load}} \): solid loading (30kg/m²)
- \( \tau_{\text{wood}} \): solid residence time

Heat exchanger area:

\[ A_{\text{heat exchanger}} = \frac{Q}{h \times (T_f - T_{\text{wat}})} \]

- \( Q \): Heat transfer flow rate
- \( h \): Heat transfer coefficient
- \( T_f \): flue gas temperature
- \( T_{\text{wat}} \): water temperature
Case study – Capital costs estimation

Drying by flue gas  
Drying by steam
Case study – Estimation of Profitability

Initial MC=1.5 kg-w/kg-wood

Drying by flue gas

Final MC=0.1, 0.3 kg-w/kg-wood

Fuel price = 14 €/MWH

Drying by steam

Final MC=0.1 kg-w/kg-wood

Fuel price = 14 €/MWH
Industrial Condensing Boiler

- Combustion of hydrocarbon-rich fuels yields two primary products, carbon dioxide and water vapor, entrained in the relatively inert nitrogen.
- Conventional boilers (non-condensing) transfer most of the sensible heat of flue gases to water.
- Condensing boiler is used to recover the latent heat of water vapour by cooling the flue gases to temperatures below the dew point
  - Indirect contact
  - Direct contact
Advantages of Condensing Boilers

- Improving the overall thermal efficiency by latent heat recovery
  - Thermal efficiency can exceed 100% with reference to the lower heating value of fuel input
  - Higher excess air ratio, lower partial pressure of water vapour, more sensible heat loss
Advantages of Condensing Boilers

- Reducing flue gas emissions through absorption in the condensate
  - >90% highly dissociated inorganic matter and particles (>10µm)
  - Lower but substantial fraction of fine particles
Technical Barriers & Solutions

- Corrosion
  - Highly corrosive condensate (H₂SO₄, HNO₃, HNO₂, NH₃, HCl, salts)
  - Durable, corrosion-resistant materials: widely applied in domestic condensing boilers

- Low return water temperature
  - Below the dew point to allow water vapour condensation
  - Large radiators & floor heating systems
  - Heat pumps
Condensing boilers with Radiator & floor heating

Return water from a heating system should be 30-50°C, well below the dew point of flue gas.

A floor heating system or large surface area radiator is required.
Condensing boilers with a heat pump

- A heat pump can be used between the condenser and the hot return water
  - Conventional electrically driven compression heat pump
  - An absorption heat pump
Case study: Condensing Boiler Design for a Biomass Heating Plant

- Objectives:
  - Thermal design of the condensing boiler
  - To investigate various technical and economic issues in relation to the condensing boiler application
- Biomass heating plant
  - Oriketo Heating Station in Finland
  - Fluidised bed boiler & flue gas condenser
  - Capacity: 40MW + 12MW (condenser)
  - Fuel: logging residue delivered mainly from final felling of spruce-dominant forests & residuals
Plant Process Parameters

<table>
<thead>
<tr>
<th>Stream No.</th>
<th>Pressure, bar</th>
<th>Temperature, °C</th>
<th>Mass flow rate, kg/s</th>
<th>Enthalpy, kJ/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>20</td>
<td>5.4</td>
<td>-17.2</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>20</td>
<td>20.9</td>
<td>-5.15</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>150</td>
<td>26.3</td>
<td>146.7 (+388.4)</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>150</td>
<td>26.3</td>
<td>146.7 (+388.4)</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>35</td>
<td>23.0</td>
<td>10.6 (+92.1)</td>
</tr>
<tr>
<td>6</td>
<td>16</td>
<td>140</td>
<td>111.6</td>
<td>590.0</td>
</tr>
<tr>
<td>7</td>
<td>16</td>
<td>30</td>
<td>111.6</td>
<td>128.0</td>
</tr>
<tr>
<td>8</td>
<td>16</td>
<td>55</td>
<td>111.6</td>
<td>231.7</td>
</tr>
<tr>
<td>9</td>
<td>1</td>
<td>35</td>
<td>3.32</td>
<td>42.4</td>
</tr>
</tbody>
</table>
## Dimensions of the condenser

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat exchanger type</td>
<td>Single tube pass, counter-current shell-and-tube exchanger (E type shell)</td>
</tr>
<tr>
<td>Tube outside diameter, $d_o$ (mm)</td>
<td>25.4</td>
</tr>
<tr>
<td>Tube inner diameter, $d_i$ (mm)</td>
<td>22.9</td>
</tr>
<tr>
<td>Tube thickness, $\delta_t$ (mm)</td>
<td>1.25</td>
</tr>
<tr>
<td>Pitch, $p_t/d_o$</td>
<td>1.75</td>
</tr>
<tr>
<td>Total tube number, $N$</td>
<td>1024</td>
</tr>
<tr>
<td>Tube layout</td>
<td>Rotated square</td>
</tr>
<tr>
<td>Shell inner diameter, $D_o$ (mm)</td>
<td>2090</td>
</tr>
<tr>
<td>Shell thickness, $\delta_s$ (mm)</td>
<td>14</td>
</tr>
<tr>
<td>Baffle type</td>
<td>Single-segmental</td>
</tr>
<tr>
<td>Baffle spacing, $B$ (mm)</td>
<td>1776</td>
</tr>
<tr>
<td>Baffle cut</td>
<td>25%</td>
</tr>
</tbody>
</table>
- Equilibrium vapour temperature vs. the difference of the specific enthalpy of the flue gas from the outlet
- At the boundaries of each zone, the heat transfer coefficients can be calculated. A mean overall heat transfer coefficient for each zone can thus be obtained

<table>
<thead>
<tr>
<th>Zone Boundaries</th>
<th>Shell-side</th>
<th>Tube-side</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>150.0</td>
<td>55.0</td>
</tr>
<tr>
<td>B</td>
<td>64.3</td>
<td>49.3</td>
</tr>
<tr>
<td>C</td>
<td>50.0</td>
<td>37.0</td>
</tr>
<tr>
<td>D</td>
<td>40.0</td>
<td>32.0</td>
</tr>
<tr>
<td>E</td>
<td>35.0</td>
<td>30.0</td>
</tr>
</tbody>
</table>
The maximum driving force for heat transfer is generally the log mean temperature difference (LMTD) when two fluid streams are in countercurrent flow.

\[
LMTD = \Delta T_{\text{lm}} = \frac{\Delta T_I - \Delta T_{II}}{\ln(\Delta T_I/\Delta T_{II})}
\]

The true mean temperature difference of flow arrangements will differ from the logarithmic mean temperature difference by a certain factor, \( F \), dependent on the flow pattern and the terminal temperatures.

<table>
<thead>
<tr>
<th>Zone</th>
<th>LMTD</th>
<th>F</th>
<th>Heat transfer rate, MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zone I</td>
<td>43.3</td>
<td>0.971</td>
<td>2.652</td>
</tr>
<tr>
<td>Zone II</td>
<td>14.0</td>
<td>0.865</td>
<td>5.757</td>
</tr>
<tr>
<td>Zone III</td>
<td>10.3</td>
<td>0.935</td>
<td>2.296</td>
</tr>
<tr>
<td>Zone IV</td>
<td>6.2</td>
<td>0.966</td>
<td>0.865</td>
</tr>
</tbody>
</table>
**Heat Resistances**

- Thermal resistances in the tube-side (including the fluid and fouling) are relatively small.
- Shell-side resistances contribute approximately 60–90% of the total resistance.
- In Zone I where no condensation occurs, the thermal resistance of the shell-side flue gas flow is dominant.
- When condensation occurs, the shell-side fouling becomes a major contributor resistance.
**Size and Pressure Drop**

- **Tube length:**
  - 63.3m for the stainless steel condensing boiler
  - 74.8m for the condensing boiler made from carbon steel

- **Heat transfer area:**
  - 4919m\(^2\) for the stainless steel condensing boiler
  - 5811m\(^2\) for the condensing boiler made from carbon steel

- **Pressure drop**
  - Tube side: 3.2 - 3.8 kPa
  - Shell side: 28.4 - 34.1 kPa

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![Graph A](image)
**Graph A:**
- Heat transfer coefficient, W/m\(^2\)K
- Carbon steel condenser
- Stainless Steel Condenser
- Zones I to IV

![Graph B](image)
**Graph B:**
- Tube length, m
- Carbon steel condenser
- Stainless Steel Condenser
- Zones I to IV
## Costs and Profitability

<table>
<thead>
<tr>
<th></th>
<th>Stainless steel condenser</th>
<th>Carbon steel condenser</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Capital costs</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Boiler cost ($)</td>
<td>2,562,000</td>
<td>852,000+50,000(PP)</td>
</tr>
<tr>
<td>Installed factor</td>
<td>1.9</td>
<td>2.2</td>
</tr>
<tr>
<td>Installed boiler cost ($)</td>
<td>4,868,000</td>
<td>1,984,000</td>
</tr>
<tr>
<td>Fan cost ($)</td>
<td>40,000</td>
<td>44,000</td>
</tr>
<tr>
<td>In total ($)</td>
<td>4,908,000</td>
<td>2,028,000</td>
</tr>
<tr>
<td><strong>O&amp;M costs</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electricity rate ($/kWh)</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Electricity ($/year)</td>
<td>580,300</td>
<td>695,800</td>
</tr>
<tr>
<td>Chemical treatment expense ($/m³)</td>
<td>0.45</td>
<td>0.45</td>
</tr>
<tr>
<td>Condensate treatment cost ($/year)</td>
<td>37,600</td>
<td>37,600</td>
</tr>
<tr>
<td>Maintenance cost factor (%)</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Maintenance cost ($/year)</td>
<td>294,480</td>
<td>121,680</td>
</tr>
<tr>
<td><strong>Benefit</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wood chips saving (t/h)</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Wood chips cost ($/tonne)</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>Fuel cost saving ($/year)</td>
<td>2,100,000</td>
<td>2,100,000</td>
</tr>
</tbody>
</table>
Costs and Profitability

- **Expected lifetime:**
  - Carbon steel (CS) condenser: 5 years
  - Stainless steel (SS) condenser: 10-15 years

- **NPV evaluation**
  - CS: 2 years cash return
  - SS: 5–7 years cash return
  - NPV of the SS condenser is more sensitive to the interest rate
**Conclusions**

- Waste flue gas and hot water (100 MW) exiting from a process industrial plant is sufficient as the heating source for wood drying for biomass combustion in a 40MW power station boiler.

- In general, for both flue gas and steam drying, 3-4 year operation is expected to give a return on the investment at a fuel price of €14/MWh.

- The average heat flux per unit heat exchanger area in the designed condenser ranges from 1.5 to 2.5 kW/m².

- NPV calculations showed that the choice of a carbon steel condenser ensured cash return in a relatively shorter period of time (i.e. 2 years) when compared to a stainless steel condenser (i.e. 5 to 7 years).
Acknowledgements

Sheffield University would like to thank EPSRC Thermal Management Consortium for the financial support for this project.

Thank You!