Industrial combustion of solid biomass fuels – state-of-the-art and relevant future developments

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   • additives to reduce ash related problems
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Latest EU policies related to biomass

- Energy & climate change package (March 2007)
  - 20% renewables by 2020
  - 20% reduction of greenhouse gas emissions by 2020
  - 20% increase of energy efficiency
  - 10% increase in biofuels by 2020

- Proposal for a Directive for the promotion of the use of energy from renewable energy sources (January 2008)

- EU Biomass action plan (2005)
  - Doubling the biomass use by 2010
    - reduction of greenhouse gas emissions by 209 Mt CO$_2$eq/year in 2010
    - employment of up to 300,000 people in 2010
    - reduction of reliance on imported energy by 6%

  - Increase share of green electricity for the EU25 from 14% to 21% in 2010

Electricity generation from biomass in EU-27

Biomass combustion technologies – classification by capacity

- Small-scale biomass combustion systems
capacity range: <100 kW\text{th}

- Medium-scale combustion systems
capacity range: 100 kW\text{th} to 10 MW\text{th}

- Large-scale combustion systems
capacity range: >10 MW\text{th}

- Co-firing of biomass in coal fired power stations
capacity range: some 100 MW\text{th}

Biomass combustion technologies – overview

- fixed bed combustion (grate furnace)
- bubbling fluidised bed combustion
- circulating fluidised bed combustion
- pulverised fuel combustion
Medium-scale biomass combustion systems

Application:
- district heating
- process heating and cooling
- CHP production

Fuels used:
- wood chips
- bark
- forest residues
- waste wood
- straw

Technologies:
- underfeed stokers
- grate-fired systems
- dust burners

Large-scale biomass combustion systems

Application:
- CHP production
- power production

Fuels used:
- bark
- forest residues
- waste wood
- straw, cereals
- fruit stones, kernels, husks, shells

Technologies:
- grate-fired systems
- fluidised beds
Application:
- power production
- CHP

Fuels used:
- forest residues
- sawdust, wood chips
- pellets
- straw
- fruit stones, kernels, husks, shells

Technologies:
- co-firing of finely milled biomass mingled with coal
- biomass co-firing in fluidised bed combustion systems
- co-firing in separate combustion units and junction of steam
- biomass gasification and utilisation of the product gas as fuel in a coal combustion system

Combustion relevant characteristics of solid biomass fuels – physical properties

<table>
<thead>
<tr>
<th>Properties</th>
<th>Effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture content</td>
<td>Storability, dry matter losses, NCV, self-ignition, plant design</td>
</tr>
<tr>
<td>NCV, GCV</td>
<td>Fuel utilisation, plant design</td>
</tr>
<tr>
<td>Volatiles</td>
<td>Thermal decomposition behaviour</td>
</tr>
<tr>
<td>Ash content</td>
<td>Dust emissions, ash manipulation, ash utilisation / disposal, combustion technology</td>
</tr>
<tr>
<td>Ash melting behaviour</td>
<td>Operational safety, combustion technology, process control system, hard deposit formation</td>
</tr>
<tr>
<td>Fungi</td>
<td>Health risks</td>
</tr>
<tr>
<td>Bulk density</td>
<td>Fuel logistics (storage, transport, handling)</td>
</tr>
<tr>
<td>Particle density</td>
<td>Thermal conductance, thermal decomposition</td>
</tr>
<tr>
<td>Physical dimension, form, size distribution</td>
<td>Hoisting and conveying, combustion technology, bridging, operational safety, drying, formation of dust</td>
</tr>
<tr>
<td>Amount of fines</td>
<td>Fuel feeding, particle entrainment</td>
</tr>
<tr>
<td>Abrasion resistance (wood pressings)</td>
<td>Quality changes, segregation, fine parts</td>
</tr>
</tbody>
</table>
Combustion relevant characteristics of solid biomass fuels – chemical properties

<table>
<thead>
<tr>
<th>Properties</th>
<th>Effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon (C)</td>
<td>GCV</td>
</tr>
<tr>
<td>Hydrogen (H)</td>
<td>GCV, NCV</td>
</tr>
<tr>
<td>Oxygen (O)</td>
<td>GCV</td>
</tr>
<tr>
<td>Chlorine (Cl)</td>
<td>HCl-, PCDD/F emissions, corrosion</td>
</tr>
<tr>
<td>Nitrogen (N)</td>
<td>NOx-, N2O emissions</td>
</tr>
<tr>
<td>Sulphur (S)</td>
<td>SOx emissions, corrosion</td>
</tr>
<tr>
<td>Fluor (F)</td>
<td>HF emissions, corrosion</td>
</tr>
<tr>
<td>Potassium (K)</td>
<td>Corrosion (heat exchangers, superheaters), lowering ash melting</td>
</tr>
<tr>
<td></td>
<td>temperature, formation of aerosols, ash utilisation (plant nutrient)</td>
</tr>
<tr>
<td>Sodium (Na)</td>
<td>Corrosion (heat exchangers, superheaters), lowering ash melting</td>
</tr>
<tr>
<td></td>
<td>temperature, formation of aerosols</td>
</tr>
<tr>
<td>Magnesium (Mg)</td>
<td>Increase of ash melting temperature, ash utilisation (plant nutrient)</td>
</tr>
<tr>
<td>Calcium (Ca)</td>
<td>Increase of ash melting temperature, ash utilisation (plant nutrient)</td>
</tr>
<tr>
<td>Phosphor (P)</td>
<td>Ash utilisation (plant nutrient), ash melting, aerosol formation</td>
</tr>
<tr>
<td>Heavy metals</td>
<td>Emissions, ash utilisation, formation of aerosols</td>
</tr>
</tbody>
</table>

Chemical compositions of different solid biomass fuels – ash, S, Cl, K

mean values and standard deviations; d.b. … dry basis
Chemical compositions of different solid biomass fuels – relevant guiding parameters

- **2S/Cl mol/mol**
  - Wood chips
  - Bark
  - Straw
  - Waste wood

- **(K+Na)/(2S+Cl) mol/mol**
  - Wood chips
  - Bark
  - Straw
  - Waste wood

- **K+Na+Zn+Pb mg/kg (d.b.)**
  - Wood chips
  - Bark
  - Straw
  - Waste wood

Mean values and standard deviations; d.b. ... dry basis

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Ash related problems in biomass combustion processes

- Ash and aerosol formation
- Slagging
- Deposit formation
- Corrosion
- Additives to reduce ash related problems
Ash formation during biomass combustion

Biomass particle
- Devolatilisation
- Char combustion, pore enlargement, ash fusion
- Ash coalescence
- Char break up
- Char burn out
- Bottom ash

Aerosol formation by fragmentation of particles
Vapourisation
Heterogeneous condensation or reaction; surface enrichment of heavy metal compounds (Pb, Zn), K₂SO₄, KCl
Ash coalescence
Char break up
Char burn out
Bottom ash

Aerosols
0.01 - 1.0 µm

Entrainment of coarse fly ash particles with the flue gas
Homogeneous nucleation
(K₂SO₄, KCl, K₂CO₃, ZnO)
Coagulation and chain agglomerate formation

Particle size distributions of fly ashes from biomass combustion

Fly ashes
Aerosols
Coarse fly ashes

Data related to dry flue gas and 13 vol.% O₂; results from grate-fired combustion systems
Typical compositions of aerosols from biomass combustion and co-firing of biomass (sawdust)

Data related to dry flue gas and 13 vol.% O₂; results from real-scale test runs.
Main features:

- Application for in-situ measurements up to 1,100°C
- Determination of the amount and particle size distribution of aerosols with the subsequent possibility of structural and chemical characterisation

Formation of molten phases – results from thermodynamic equilibrium analyses

Results of thermodynamic equilibrium calculations concerning the grate ash; ash composition data for the simulations were taken from real-scale test runs with bark and straw at grate-fired furnaces.
The blue line shows a typical biomass fly ash. Often fly ash is almost pure K₂SO₄, which has a high melting point, 1068°C.

If carbonate is formed the first melting point decreases to 940°C, if chlorides form to 643°C.

Small amounts of Na (red curve) decrease the first melting point to 609°C.

Presence of Pb and Zn, even in small amounts compared to K and Na, results in molten phases at such low temperatures as 196°C.

That low first melting points can cause serious corrosion and contribute to rapid build-up of deposits on heat transfer surfaces.

Results based on a new thermodynamic model developed by Abo University Academy within the EU FP6 project BIOASH.

CFD simulation of aerosol formation

Explanations: 1st and 2nd radiative duct of a biomass fired water tube steam boiler (nominal thermal load: 40MWth); reactive sulphur is represented by SO₃; fuel: waste wood; aerosol species considered: K₂SO₄, K₂CO₃, KCl, (KCl)₂, NaSO₄, NaCl, (NaCl)₂, PbCl₂, PbO, ZnCl₂, ZnO
Solid phase reactions involving alkali metal chlorides

\[ 2KCl(s) + SO_2(g) + 0.5 O_2(g) + H_2O(g) \rightarrow K_2SO_4(s) + 2HCl(g) \]

→ highly relevant

Reactions involving molten alkali metal and other chlorides

→ relevant

<table>
<thead>
<tr>
<th>System</th>
<th>Melting/eutectic temperature (°C)</th>
<th>Composition at the eutectic point (mole% alkali)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NaCl</td>
<td>801</td>
<td>—</td>
</tr>
<tr>
<td>KCl</td>
<td>772</td>
<td>—</td>
</tr>
<tr>
<td>FeCl₂</td>
<td>677</td>
<td>—</td>
</tr>
<tr>
<td>CrCl₂</td>
<td>845</td>
<td>—</td>
</tr>
<tr>
<td>NaCl–FeCl₂</td>
<td>370–374</td>
<td>c. 56</td>
</tr>
<tr>
<td>KCl–FeCl₂</td>
<td>340–393</td>
<td>45.8–91.8</td>
</tr>
<tr>
<td>NaCl–CrCl₂</td>
<td>437</td>
<td>53.7</td>
</tr>
<tr>
<td>KCl–CrCl₂</td>
<td>462–457</td>
<td>36–70</td>
</tr>
</tbody>
</table>


<table>
<thead>
<tr>
<th>N₂ CO₂ O₂ SO₂ SO₃ MeCl (g)</th>
<th>flue gas</th>
<th>SO₂ O₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>sulfates/chlorides silicates</td>
<td>Cl₂ + Na₂SO₄ ← SO₂ + O₂ + 2 NaCl</td>
<td></td>
</tr>
<tr>
<td>Fe₃O₄ + ash</td>
<td>outer oxide layer</td>
<td>3 Fe₃O₄ ← 1/2 O₂ + 2 Fe₃O₄</td>
</tr>
<tr>
<td>Fe₃O₄ + FeS</td>
<td>inner oxide layer</td>
<td>3 Cl₂ + Fe₆O₁₀ ← 2 O₂ + 3 FeCl₂</td>
</tr>
<tr>
<td>FeCl₂</td>
<td>corrosion front</td>
<td>4 Cl₂ + FeS + Fe₆O₁₀ ← SO₂ + O₂ + 4 FeCl₂</td>
</tr>
<tr>
<td>low alloyed steel</td>
<td>tube wall</td>
<td>Cl₂ + Fe ← FeCl₂</td>
</tr>
</tbody>
</table>

\[ p_{FeCl₂} = 10^{-5} - 10^{-3} \text{ bar at 400 - 530 °C} \]
Additives applied in biomass combustion systems

<table>
<thead>
<tr>
<th>Purpose</th>
<th>Additive</th>
<th>State-of-application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sulphation of chlorides to reduce corrosion</td>
<td>ChlorOut (ammonium sulphate)</td>
<td>Demonstration</td>
</tr>
<tr>
<td>Alkaline metal catchers to reduce aerosol formation</td>
<td>Kaolin</td>
<td>R&amp;D</td>
</tr>
<tr>
<td>Additives to increase ash melting temperatures</td>
<td>Ca-based</td>
<td>R&amp;D</td>
</tr>
<tr>
<td>Mg-based</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Additives to reduce SO$_2$-HCl- and PCDD/F-emissions</td>
<td>Limestone</td>
<td>State-of-the-art</td>
</tr>
<tr>
<td>Sodium bicarbonate</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Activated charcoal</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Additives for NO$_x$ emission reduction</td>
<td>Urea</td>
<td>State-of-the-art</td>
</tr>
<tr>
<td>NH$_3$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

CFD simulation of biomass combustion plants — model overview

Models for gas phase combustion and NO$_x$ formation
- Turbulence models
- Turbulence-chemistry interaction models
- Reaction mechanisms

Finite cell model for convective heat exchangers
- For fire tube boilers, water tube and steam boilers, thermal oil boilers
- Consideration of flow, heat transfer, pressure distribution; calculation of tube surface temperatures
- Link with ash deposit model (in progress)

Models for solid biomass conversion
- Single particle conversion and volatiles release
- Multiphase modelling for particle-particle and particle-gas interactions in packed beds (and entrained flows)

Models for ash deposit and aerosol formation
- Direct wall condensation, deposition of fly ash particles
- Aerosol formation and deposition
- Erosion
- Deposit growth and influence on heat transfer
Layer model (LM) for thermally thick biomass particles

- Particle is separated in 4 discrete layers
- Each layer corresponds to one conversion step:
  1 – Drying
  2 – Devolatilisation
  3 – Char burnout
  4 – Inert heating of ash layer
- Boundaries between the layers correspond to reaction fronts which move towards the particle centre
- Model variables: radiiuses of conversion fronts \( r_i \) and temperatures of layers \( T_i \)
- Temperature and species gradients in the particle are considered
- Simultaneous occurrence of single processes is considered
- Advantage of layer model: more exact calculation of particle conversion compared to the standard model for thermally thin particles (Discrete Phase Model) at considerably reduced calculation times compared to a detailed simulation.

Structure of overall model

1. Models for single biomass particle conversion
   - Modelling of thermally thin particles – standard FLUENT model adapted for biomass
   - Modelling of thermally thick particles – Layer Model (LM)

   - Lagrangian Discrete Phase Model (DPM) for dilute discrete phase (volume fraction < 10%)
   - Hybrid Euler-Lagrange Model / Dense Discrete Phase Model (DDPM) for dense discrete phases (volume fraction > 10%)

3. Gas phase combustion modelling
   - Advantages of overall model
     - Sub-models can be combined arbitrarily
     - Model is suitable for packed bed combustion and for pulverised biomass combustion
Processes and applied sub-models

(1) ANS turbulence models
- 2-equation models (k-ε Models: Standard k-ε Model, Realizable k-ε Model; k-ω Models) for weakly and moderately anisotropic turbulent flows
- Reynolds stress models for highly anisotropic turbulent flows

(2) Models for turbulence-chemistry interactions
- Eddy Dissipation Model in combination with global reaction mechanisms for mixing dominated processes
- Eddy Dissipation Concept in combination with detailed and reduced reaction mechanisms for consideration of complex turbulence-chemistry interactions

(3) Reaction mechanisms
- Global methane 3-step reaction mechanism
- Reduced Kilpinen 97-Skeletal mechanism (subsets for combustion and N-chemistry) validated for gas phase chemistry in biomass combustion systems
- Detailed Kilpinen 92 + Kilpinen 97 (subsets for combustion and N-chemistry) validated for gas phase chemistry in biomass combustion systems

CFD simulation of ash deposit formation – deposition of coarse fly ash particles and direct wall condensation

Deposition mass fluxes [mg/m²s] to the walls of a biomass grate furnace and the flame tube of a fire tube boiler

Explanations: fuel waste wood, nominal thermal load 440 kWth; operation duration: 1 hour
Trajectories of coarse fly ash particles with different size (Stokes number St).

Mass fraction of impacting particles in dependence of tube row and particle size (Stokes number St).


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Gaseous and particulate emissions - strategies for emission reduction (I)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Measures for emission reduction</th>
</tr>
</thead>
</table>
| CO, OGC, PAH | • sufficient residence time at furnace temperatures above 850°C  
|               | • good mixing of flue gases with the combustion air  
|               | • sufficient particle/ash burnout (TOC <5 wt%) |
| PCDD/F | • utilise fuels with low Cl-contents  
|         | • complete combustion of the flue gas and the fly ash particles  
|         | • avoid entrainment of incompletely combusted fuel particles  
|         | • precipitation temperature of fly ashes > 600°C or < 250°C  
|         | • secondary measure: sorption with activated carbon |
## Gaseous and Particulate Emissions - Strategies for Emission Reduction (II)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Measures for Emission Reduction</th>
</tr>
</thead>
</table>
| **HCl, SO₂** | • utilise fuels with low S- and Cl-contents  
• secondary measures: dry sorption systems or scrubbers |
| **Aerosols** | • utilise fuels with low K, Na and volatile heavy metal contents  
• reduce release of easily volatile inorganic species  
• secondary measures: baghouse filters  
  electrostatic precipitators |
| **Heavy Metals** | • utilise fuels with low heavy metals contents  
(chemically untreated biomass)  
• application of highly efficient aerosol precipitators  
(highly efficient baghouse filters)  
• dry sorption for Hg emission control |

### Relation Between Fuel N Content, NOₓ Emission Reduction Measures and NOₓ Emissions

![Graph](image)

**Explanations:**
- NOₓ calculated as NO₂ and related to dry flue gas and 11 vol.% O₂
- NOₓ calculated as NO₂ and related to dry flue gas and 11 vol.% O₂

**Combustion Processes:**
- Conventional Combustion
- Low-NOₓ Combustion with Air Staging
- SNCR Process
- SCR Process
Conversion of the fuel-N to N contained in NO\textsubscript{x}-precursors during combustion of different biomass fuels

Explanations: TFN … total fixed nitrogen = Nitrogen bound in NO, NO\textsubscript{2}, NH\textsubscript{3}, HCN and N\textsubscript{2}O

CFD Simulation of NO\textsubscript{x} formation – model overview

- Release of the N-species (NO, NH\textsubscript{3} and HCN) from the solid fuel on the grate encountered for by the empirical fuel bed model
- CFD simulation based on the Eddy Dissipation Concept and the Skeletal Kilpinen 97 reaction mechanism (25 species, 104 reactions)
- ISAT (In-Situ Adaptive Tabulation) algorithm used for the tabulation of reaction kinetics during run-time for the reduction of calculation time
- Advancements compared to the CFD models based on global reaction kinetics for complex NO\textsubscript{x} chemistry:
  - Deeper insight into the local course of the processes by the prediction of the radical pool important in the NO\textsubscript{x} formation
  - Detailed analysis of the interactions between the flow field and nitrogen chemistry possible
Profiles of NO and N₂ net production rate (indicator for NOₓ reduction) in a biomass grate furnace and comparison measurement/simulation.

Explanations: nominal thermal load 440 kWth; fuel fibre board, fuel nitrogen content 6.5 [wt.% d.b.]

CFD simulation of NOₓ formation – grate furnace

<table>
<thead>
<tr>
<th></th>
<th>Measurement</th>
<th>Simulation</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>7.5 ± 10.2</td>
<td>4.5</td>
<td>ppmV d.b.</td>
</tr>
<tr>
<td>NO</td>
<td>391.5 ± 68.0</td>
<td>417.4</td>
<td>ppmV d.b.</td>
</tr>
<tr>
<td>NO₂</td>
<td>-</td>
<td>8.4</td>
<td>ppmV d.b.</td>
</tr>
<tr>
<td>NH₃</td>
<td>-</td>
<td>1.6 E-07</td>
<td>ppmV d.b.</td>
</tr>
<tr>
<td>HCN</td>
<td>-</td>
<td>3.5 E-05</td>
<td>ppmV d.b.</td>
</tr>
</tbody>
</table>

CFD simulation of NOₓ formation (3) – small-scale packed-bed furnace

NO profile and cross-section averaged TFN/TFN_in ratio in a small-scale packed-bed furnace.

Explanations: boiler output 15 kW; fuel: softwood pellets; fuel nitrogen content: 0.05 [wt.% d.b.]; TFN...total fixed nitrogen encountered in NO, NH₃, HCN, N₂O and NO₂; TFN_in...total fixed nitrogen released from the fuel bed.
Still a high potential for optimisation is given.

Currently applied control strategies

- mostly a decentralised structure
  (one input variable is coupled with one output and controlled separately)

- they do not consider the coupled and non-linear nature of control loops in biomass furnaces

- do not utilise the full potential of well engineered plants

Neural network based control

+ experimentally determined model
- no consideration of the physical coherences
- resulting model strongly depends on training data → validity is not guaranteed for every state

Fuzzy logic based control

+ quick development of a controller based on experience
- states which are not considered by rules can lead to malfunctions
- no deterministic procedure for the design of a fuzzy controller → liberties in the realisation of fuzzy controllers can degrade the results significantly

Model based control strategies

+ consideration of essential physical characteristics of biomass furnaces
+ well established theory for the controller design
+ state-of-the-art control methods for nonlinear systems can be applied
- labour-intensive approach if no applicable mathematical model is available
### Ongoing research and future R&D topics

<table>
<thead>
<tr>
<th>State of science</th>
<th>Future R&amp;D</th>
</tr>
</thead>
<tbody>
<tr>
<td>conventional biomass fuels (wood fuels, straw)</td>
<td>new biomass fuels annual crops, short rotation plants, waste materials from the agricultural and the food industry, etc.</td>
</tr>
<tr>
<td>modern biomass combustion technologies</td>
<td>next generation biomass combustion systems towards zero emission technologies towards new process control systems</td>
</tr>
<tr>
<td>conventional CHP technologies</td>
<td>advanced highly efficient systems supercritical boilers combined cycles</td>
</tr>
<tr>
<td>single model development</td>
<td>virtual biomass conversion plant</td>
</tr>
</tbody>
</table>

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**Thank you for your attention**

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