

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

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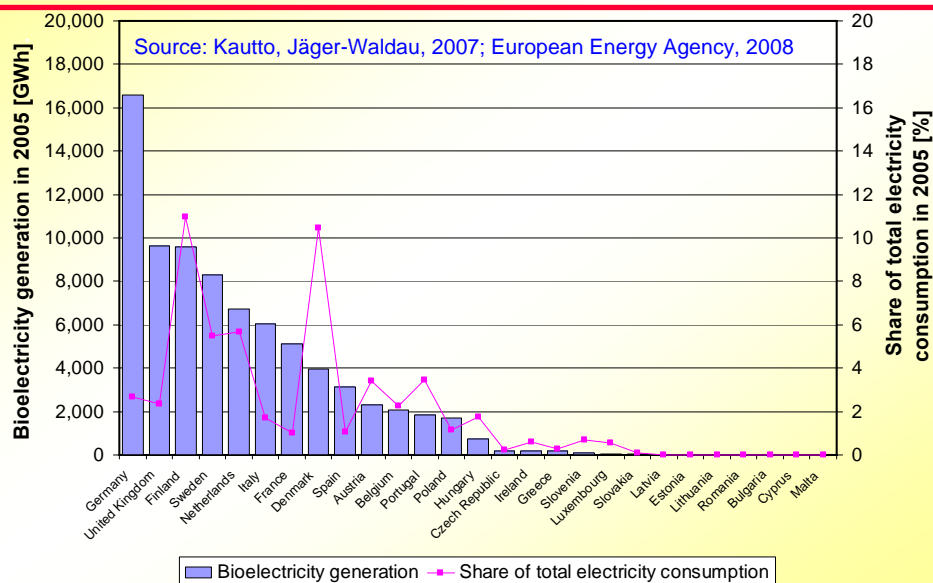
Contents

- Thermal biomass utilisation in Europe
- Biomass combustion and biomass / coal co-firing technologies
- Relevant characteristics of biomass fuels
- Ash formation and ash related problems
 - ash and aerosol formation
 - slagging, deposit formation and corrosion
 - additives to reduce ash related problems
- CFD as an efficient tool to design and optimise biomass combustion systems
- Gaseous emissions under special consideration of NO_x
- Intelligent process control systems
- Relevant future R&D trends



- **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_{2eq}/year in 2010
 - employment of up to 300,000 people in 2010
 - reduction of reliance on imported energy by 6%
- **EU RES-e Directive (2001)**
 - Increase share of green electricity for the EU25 from 14% to 21% in 2010

3



4



Biomass combustion technologies – classification by capacity

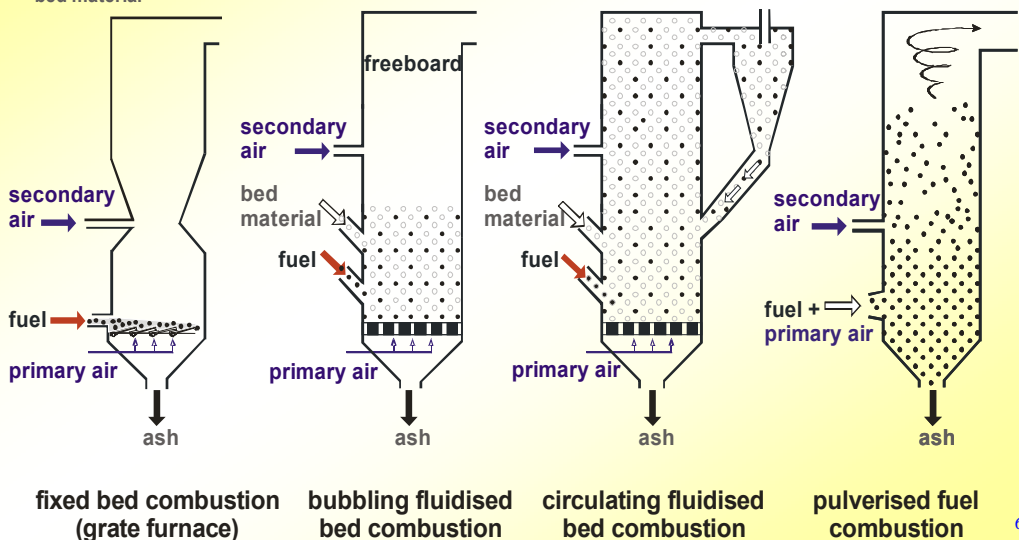
- **Small-scale biomass combustion systems**
capacity range: $<100 \text{ kW}_{\text{th}}$
- **Medium-scale combustion systems**
capacity range: $100 \text{ kW}_{\text{th}}$ to $10 \text{ MW}_{\text{th}}$
- **Large-scale combustion systems**
capacity range: $>10 \text{ MW}_{\text{th}}$
- **Co-firing of biomass in coal fired power stations**
capacity range: some $100 \text{ MW}_{\text{th}}$

5



Biomass combustion technologies – overview

- fuel
- bed material



6



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Medium-scale biomass combustion systems

Application:

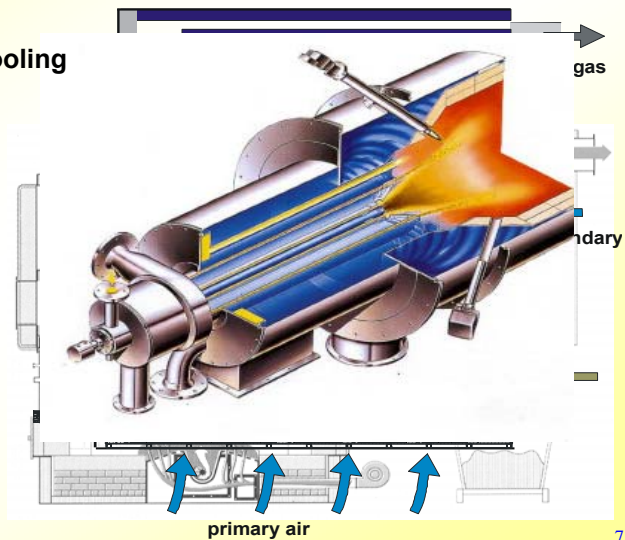
- district heating
- process heating and cooling
- CHP production

Fuels used:

- wood chips
- bark
- forest residues
- waste wood
- straw

Technologies:

- underfeed stokers
- grate-fired systems
- dust burners



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Large-scale biomass combustion systems

Application:

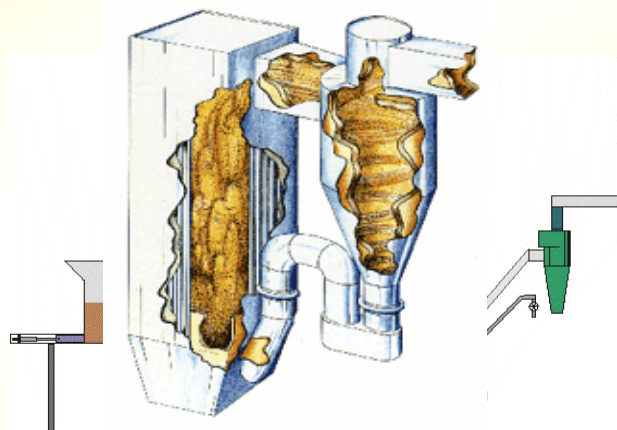
- CHP production
- power production

Fuels used:

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

Technologies:

- grate-fired systems
- fluidised beds



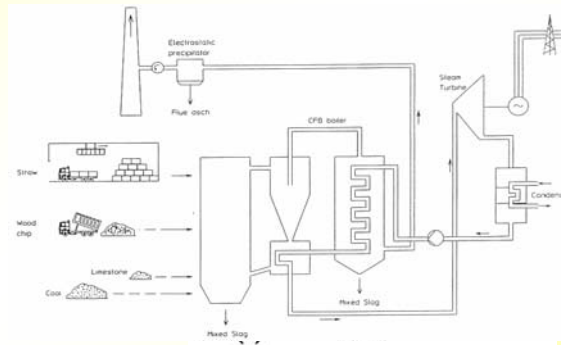
Biomass co-firing in coal fired power stations

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

9

Combustion relevant characteristics of solid biomass fuels – physical properties

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

10



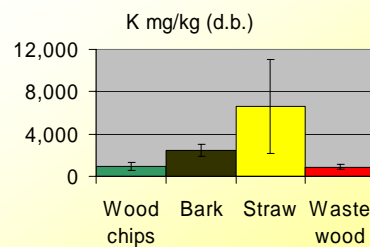
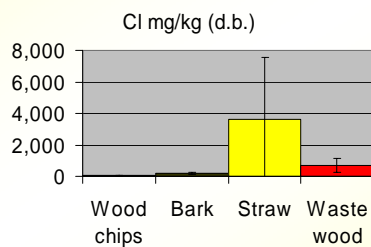
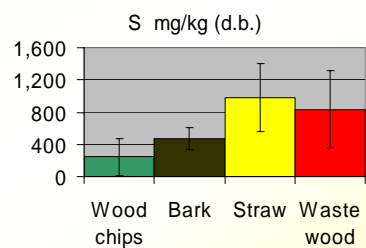
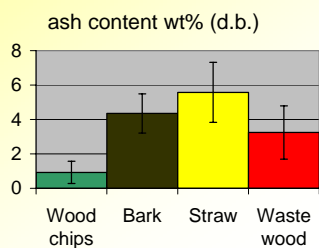
Combustion relevant characteristics of solid biomass fuels – chemical properties

Properties	Effects
Carbon (C)	GCV
Hydrogen (H)	GCV, NCV
Oxygen (O)	GCV
Chlorine (Cl)	HCl-, PCDD/F emissions, corrosion
Nitrogen (N)	NO _x -, N ₂ O emissions
Sulphur (S)	SO _x emissions, corrosion
Fluor (F)	HF emissions, corrosion
Potassium (K)	Corrosion (heat exchangers, superheaters), lowering ash melting temperature, formation of aerosols, ash utilisation (plant nutrient)
Sodium (Na)	Corrosion (heat exchangers, superheaters), lowering ash melting temperature, formation of aerosols
Magnesium (Mg)	Increase of ash melting temperature, ash utilisation (plant nutrient)
Calcium (Ca)	Increase of ash melting temperature, ash utilisation (plant nutrient)
Phosphor (P)	Ash utilisation (plant nutrient), ash melting, aerosol formation
Heavy metals	Emissions, ash utilisation, formation of aerosols

11



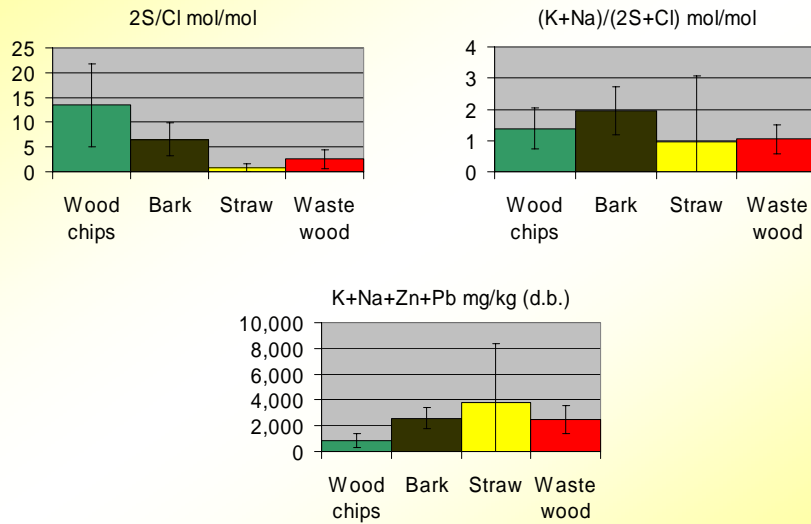
Chemical compositions of different solid biomass fuels – ash, S, Cl, K



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

12

Chemical compositions of different solid biomass fuels – relevant guiding parameters



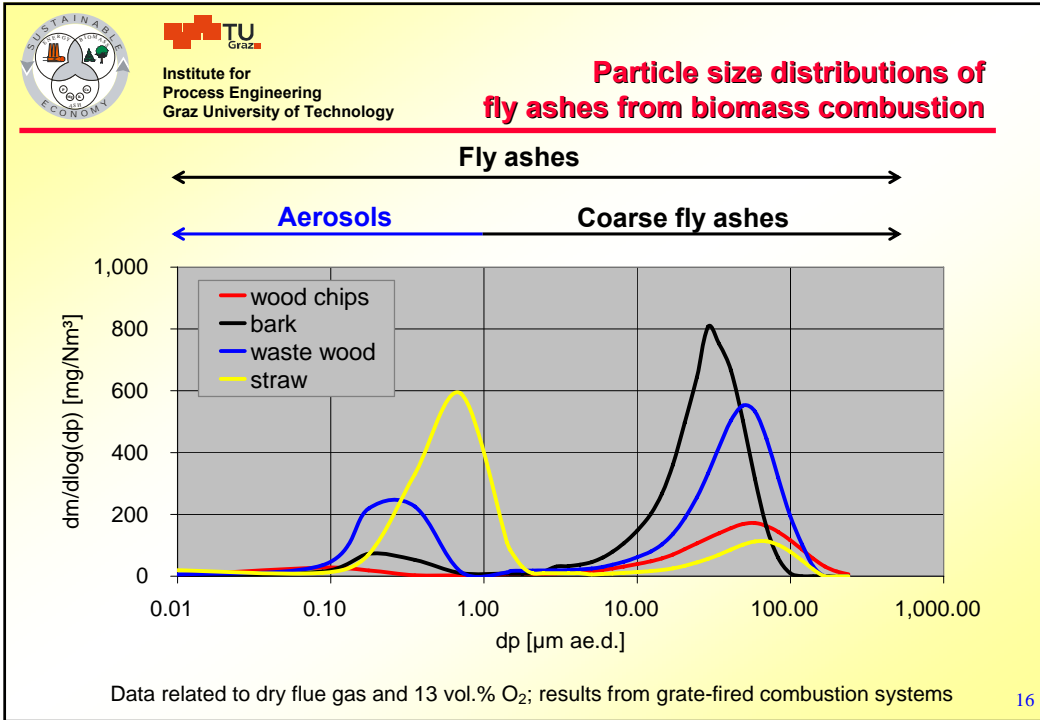
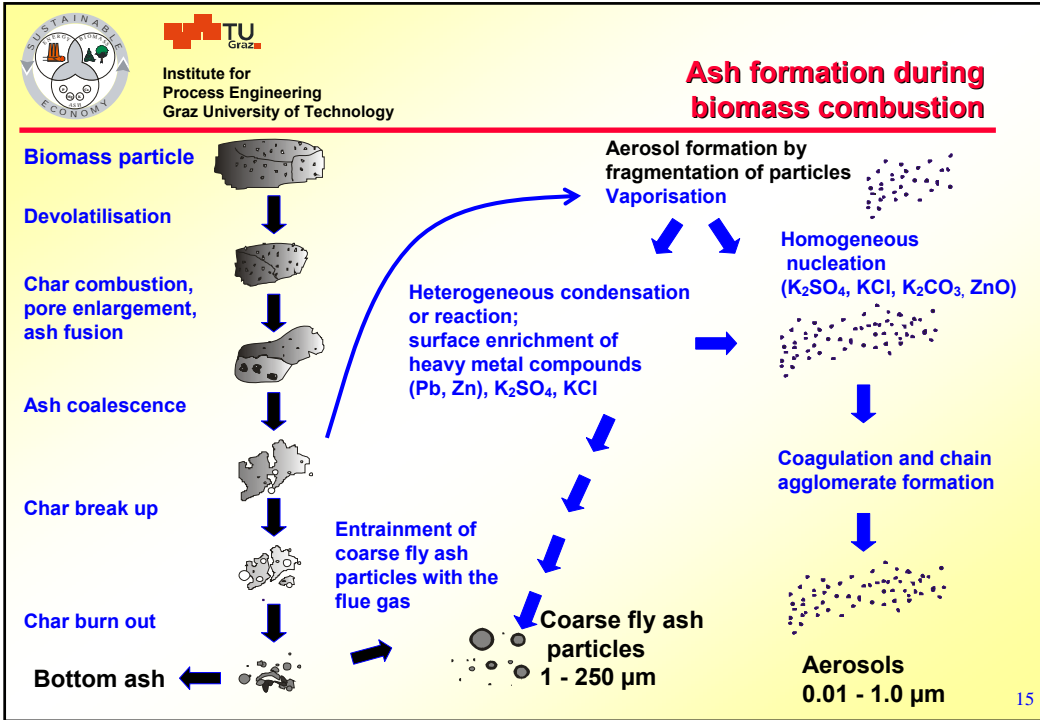
mean values and standard deviations; d.b. ... dry basis

13

Ash related problems in biomass combustion processes

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

14



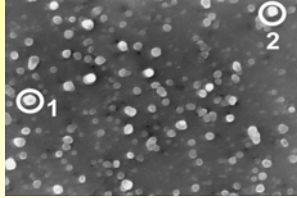


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Aerosols – shape and chemical composition

Softwood (spruce)

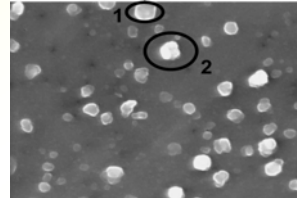
(picture width: 4 µm)



	1	2
	atom%	
K	28.5	27.1
Na	2.7	7.6
S	9.0	9.2
Cl	1.6	5.4
Zn	7.3	2.8
O	50.4	47.8

Hardwood (beech)

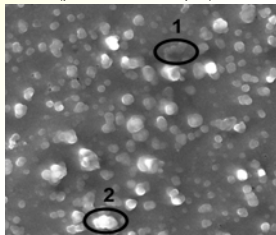
(picture width: 2.9 µm)



	1	2
	atom%	
K	34.6	38.9
Na	1.5	5.1
S	9.7	5.7
Cl	5.7	8.8
O	47.8	40.3

Bark

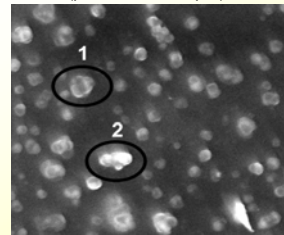
(picture width: 4 µm)



	1	2
	atom%	
K	27.3	37.1
S	3.7	4.7
Cl	18.1	34.5
Zn	3.4	2.4
Ca	1.3	0.0
O	40.7	21.3

Waste wood

(picture width: 2 µm)



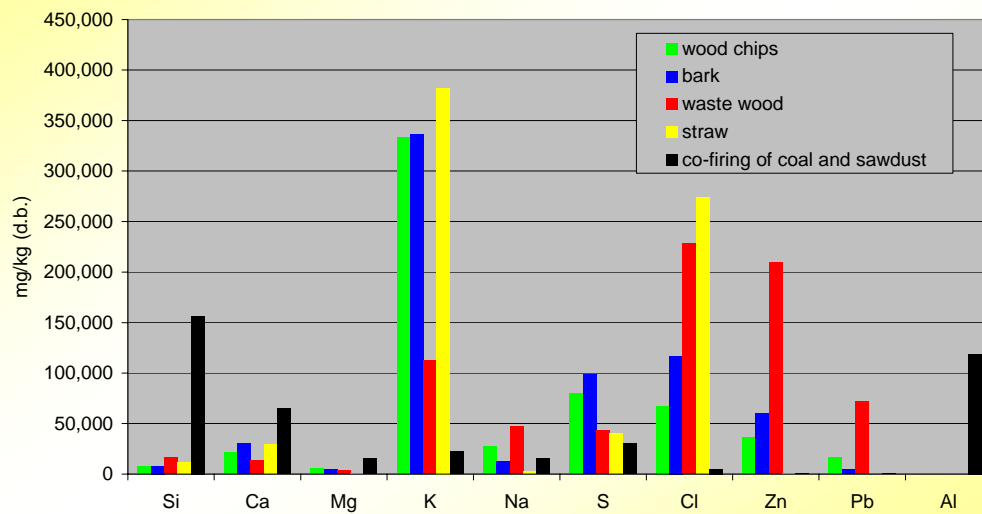
	1	2
	atom%	
K	8.7	13.1
Na	4.4	0.0
S	0.0	3.2
Cl	36.6	44.6
Zn	12.6	10.4
Pb	25.2	6.5
O	12.6	22.5

17



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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

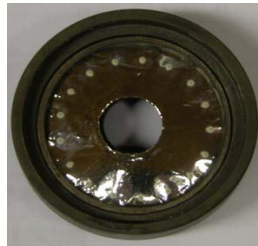
18

Main features:

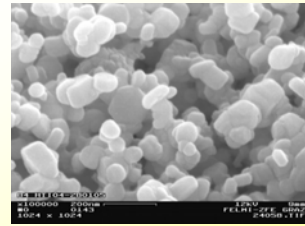
- Application for in-situ measurements up to 1,100°C
- Determination of the amount and particle size distribution of aerosols with the subsequent possibility of structural and chemical characterisation



high-temperature impactor
during and after measurement

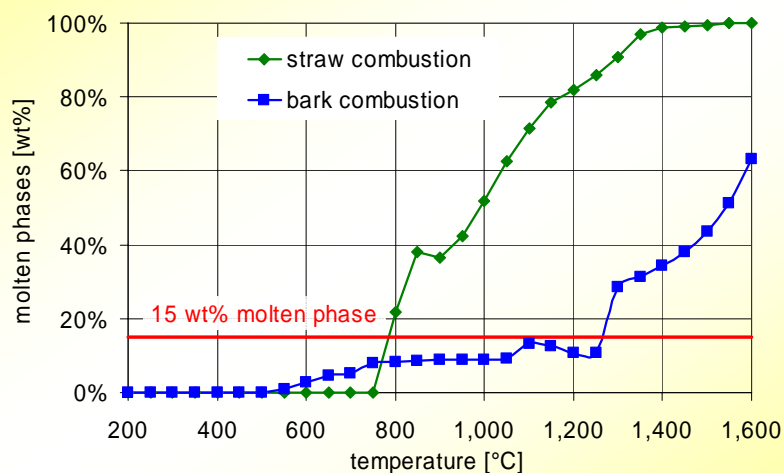


sampling foil with particles



SEM image of Zn-particles sampled
in the hot furnace during waste
wood combustion

19



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

20



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Influence of Pb and Zn on ash melting

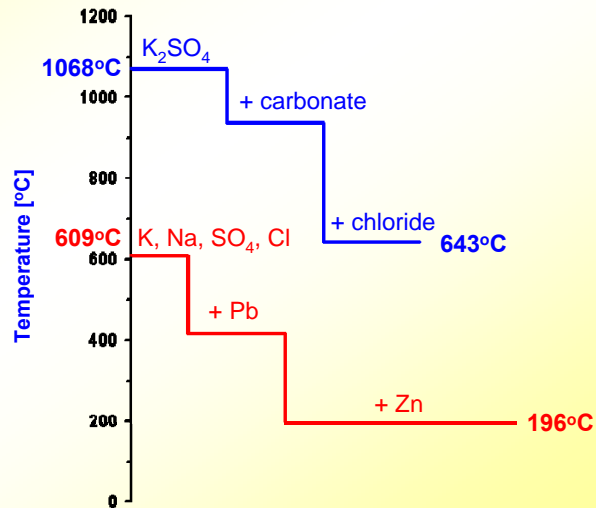
The blue line shows a typical biomass fly ash. Often fly ash is almost pure K_2SO_4 , which has a high melting point, $1068^\circ C$.

If **carbonate** is formed the first melting point decreases to $940^\circ C$, if **chlorides** form to $643^\circ C$.

Small amounts of **Na** (red curve) decrease the first melting point to $609^\circ C$.

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

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

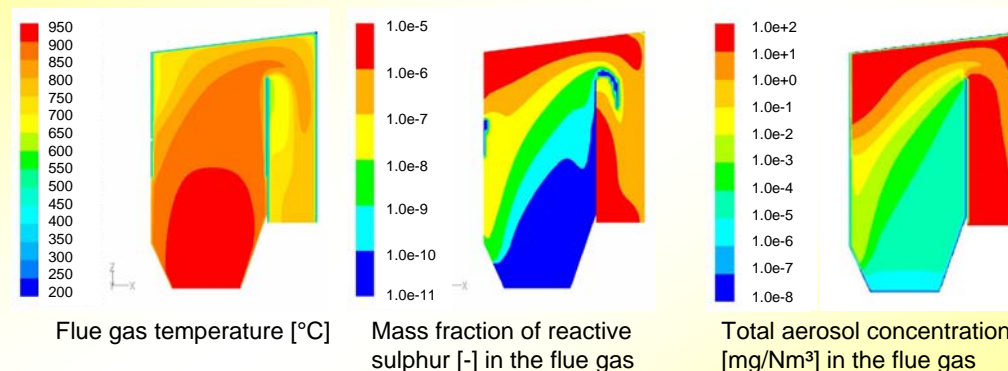


Results based on a new thermodynamic model developed by Abo University Academy within the EU FP6 project BIOASH₂₁



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CFD simulation of aerosol formation

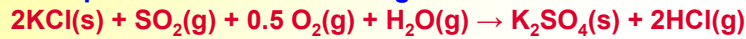


Explanations: 1st and 2nd radiative duct of a biomass fired water tube steam boiler (nominal thermal load: $40MW_{th}$); reactive sulphur is represented by SO_3 ; fuel: waste wood; aerosol species considered: K_2SO_4 , K_2CO_3 , KCl, $(KCl)_2$, $NaSO_4$, NaCl, $(NaCl)_2$, $PbCl_2$, PbO, $ZnCl_2$, ZnO)



Ash related problems in biomass combustion processes – corrosion, relevant mechanisms

➤ **Solid phase reactions involving alkali metal chlorides**



→ highly relevant

➤ **Reactions involving molten alkali metal and other chlorides**

→ relevant

System	Melting/eutectic temperature (°C)	Composition at the eutectic point (mole% alkali)
NaCl	801	—
KCl	772	—
FeCl ₂	677	—
CrCl ₂	845	—
NaCl–FeCl ₂	370–374	c. 56
KCl–FeCl ₂	340–393	45.8–91.8
NaCl–CrCl ₂	437	53.7
KCl–CrCl ₂	462–457	36–70

23



Ash related problems in biomass combustion processes – corrosion, active oxidation mechanism

N ₂ , CO ₂ , O ₂	flue gas	
SO ₂ , SO ₃ , MeCl (g)		SO ₂ O ₂
sulfates/chlorides silicates	ash layer	Cl ₂ + Na ₂ SO ₄ ← SO ₂ + O ₂ + 2 NaCl
Fe ₂ O ₃ + ash	outer oxide layer	↓ ↓
Fe ₃ O ₄ + FeS	inner oxide layer	3 Fe ₂ O ₃ ← 1/2 O ₂ + 2 Fe ₃ O ₄
FeCl ₂	corrosion front	3 Cl ₂ + Fe ₃ O ₄ ← 2 O ₂ + 3 FeCl ₂
		4 Cl ₂ + FeS + Fe ₃ O ₄ ← SO ₂ + O ₂ + 4 FeCl ₂
		Cl ₂ + Fe → FeCl ₂
low alloyed steel	tube wall	P _{FeCl₂} = 10 ⁻⁵ - 10 ⁻³ bar at 400 - 530 °C

Explanations: literature source: H.-H. Reichel and U. Schirmer,
Waste incineration plants in the FGR,
in: Werkstoffe und Korrosion, 40, 135-141, (1989)

24



Additives applied in biomass combustion systems

Purpose	Additive	State-of-application
Sulphation of chlorides to reduce corrosion	ChlorOut (ammonium sulphate)	Demonstration
Alkaline metal catchers to reduce aerosol formation	Kaolin	R&D
Additives to increase ash melting temperatures	Ca-based Mg-based	R&D
Additives to reduce SO ₂ -HCl- and PCDD/F-emissions	Limestone Sodium bicarbonate Activated charcoal	State-of-the-art
Additives for NO _x emission reduction	Urea NH ₃	State-of-the-art

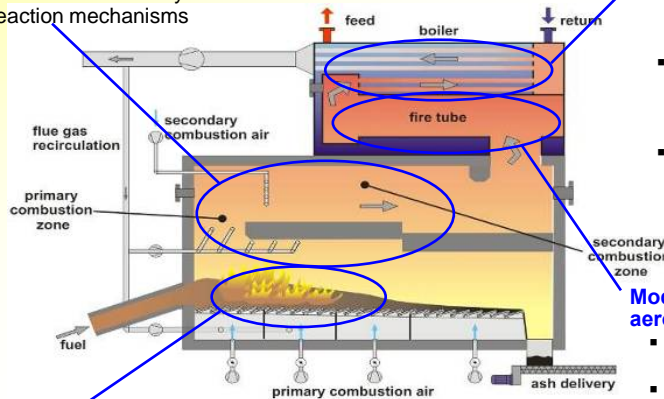
25



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 ash deposit and aerosol formation

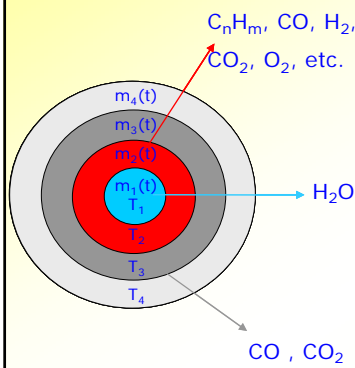
- Direct wall condensation, deposition of fly ash particles
- Aerosol formation and deposition
- Erosion
- Deposit growth and influence on heat transfer

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)

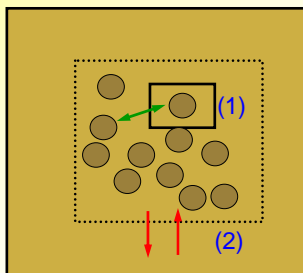
26

Layer model (LM) for thermally thick biomass particles



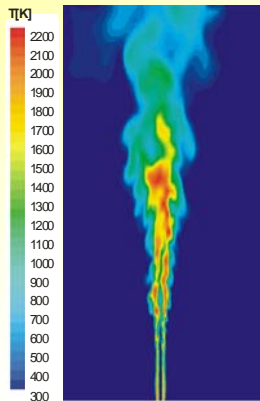
- Particle is separated in 4 discrete layers
- Each layer corresponds to one conversion step
 - 1 – Drying
 - 2 – Devolatilisation
 - 3 – Char burnout
 - 4 – Inert heating of ash layer
- Boundaries between the layers correspond to reaction fronts which move towards the particle centre
- Model variables: radiuses 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 simulation²⁷

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)
- (2) Multiphase modelling for particle-particle and particle-gas interactions
 - 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

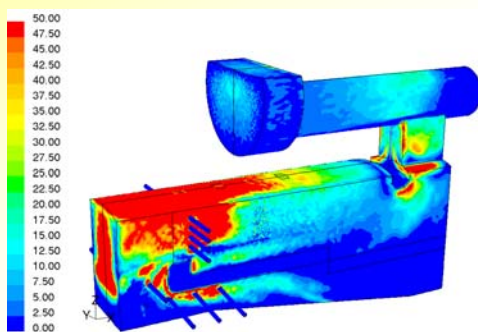
- **Eddy Dissipation Model** in combination with global reaction mechanisms for mixing dominated processes
- **Eddy Dissipation Concept** in combination with detailed and reduced reaction mechanisms for consideration of complex turbulence-chemistry interactions

(3) Reaction mechanisms

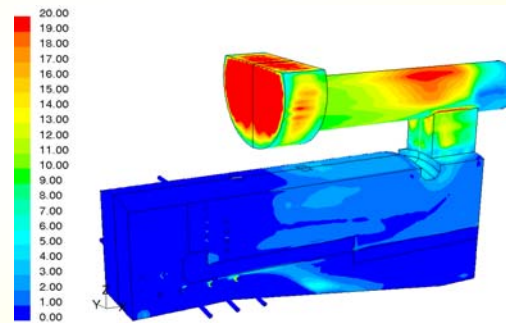
- **Global methane 3-step reaction mechanism**
- **Reduced Kilpinen 97-Skeletal mechanism** (subsets for combustion and N-chemistry) validated for gas phase chemistry in biomass combustion systems
- **Detailed Kilpinen 92 + Kilpinen 97** (subsets for combustion and N-chemistry) validated for gas phase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

29

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



coarse fly ash particles

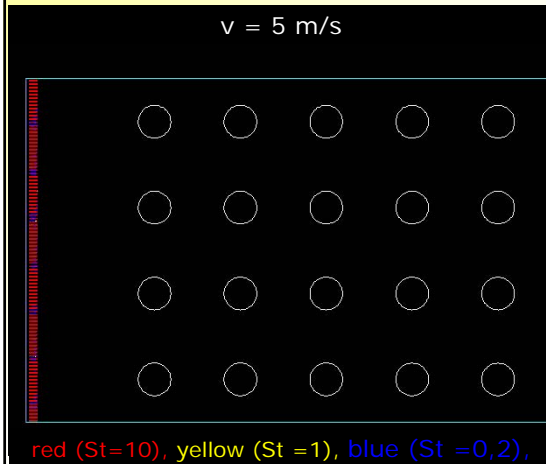


direct wall condensation

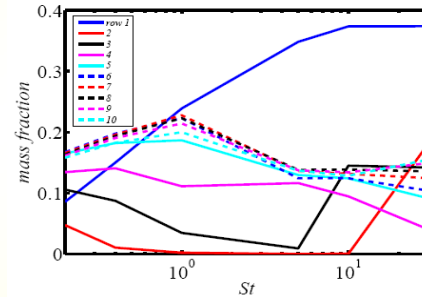
Explanations: fuel waste wood, nominal thermal load 440 kW_{th}; operation duration: 1 hour

30

CFD simulation of ash deposit formation – link of deposit formation model with heat exchanger model



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)

Source: Kuerten J.G.M., Scharler R., Schulze K.,
Oberberger I.: Numerical simulation of ash particle
impaction in tube bundles; paper submitted for publication in
the International Journal of Heat and Fluid Flow

31

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

Parameter Measures for emission reduction

**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 ($\text{TOC} < 5 \text{ wt}\%$)

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 $> 600^\circ\text{C}$ or $< 250^\circ\text{C}$
- secondary measure: sorption with activated carbon

32



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

Parameter Measures for emission reduction

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

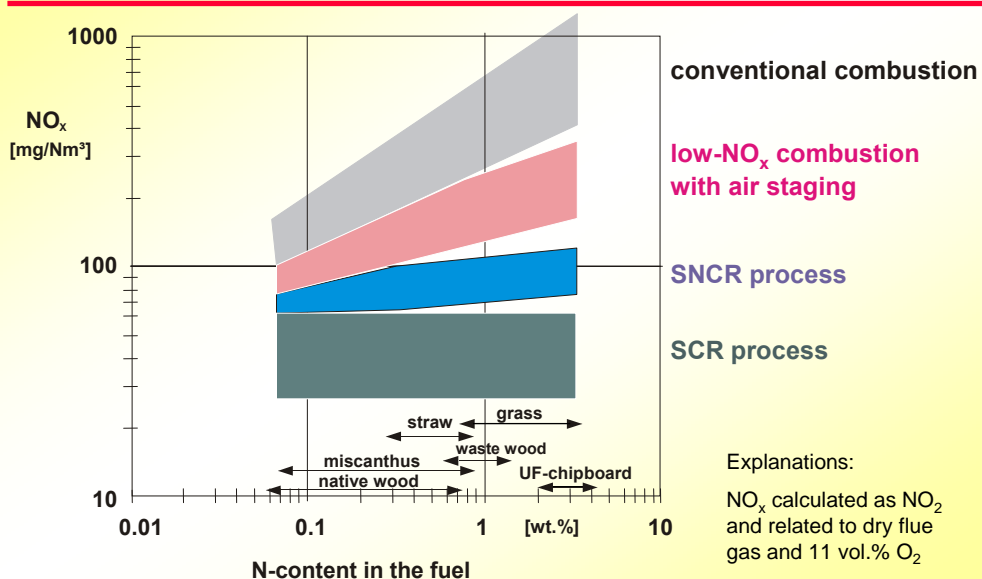
Heavy metals

- 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

33

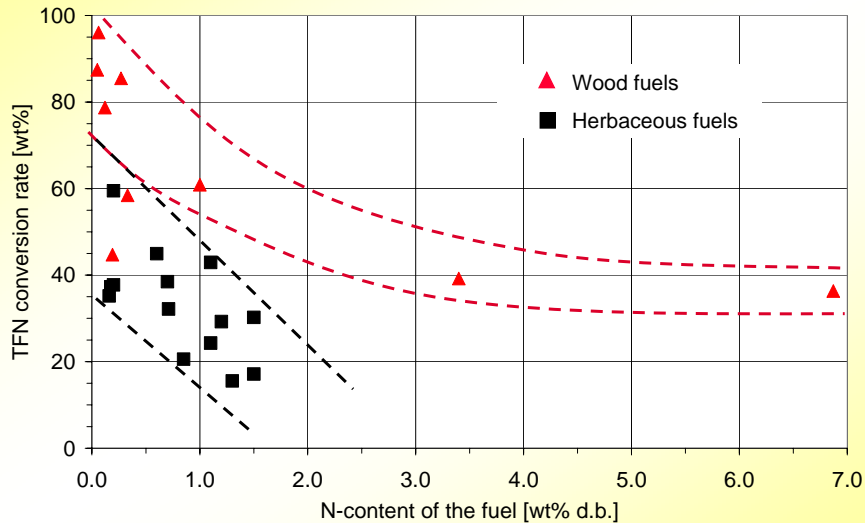


Relation between fuel N content, NO_x emission reduction measures and NO_x emissions



34

Conversion of the fuel-N to N contained in NO_x -precursors during combustion of different biomass fuels



Explanations: TFN ... total fixed nitrogen = Nitrogen bound in NO , NO_2 , NH_3 , HCN and N_2O

35

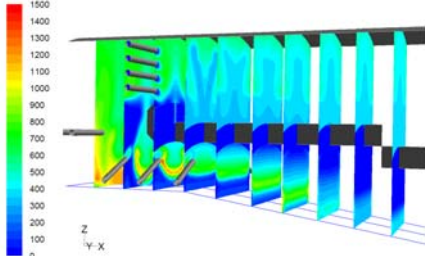
CFD Simulation of NO_x formation – model overview

- Release of the N-species (NO , NH_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_x chemistry:
 - Deeper insight into the local course of the processes by the prediction of the radical pool important in the NO_x formation
 - Detailed analysis of the interactions between the flow field and nitrogen chemistry possible

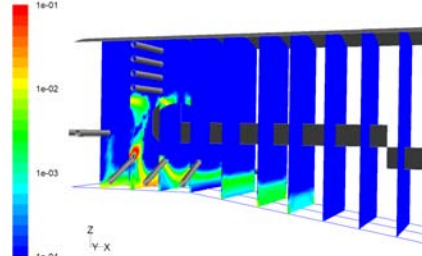
36

CFD simulation of NO_x formation – grate furnace

NO [ppmv]



N₂ net production rate [kg/m³s]



	Measurement	Simulation	Unit
CO	7.5 ± 10.2	4.5	ppmV d.b.
NO	391.5 ± 68.0	417.4	ppmV d.b.
NO ₂	-	8.4	ppmV d.b.
NH ₃	-	1.6 E-07	ppmV d.b.
HCN	-	3.5 E-05	ppmV d.b.

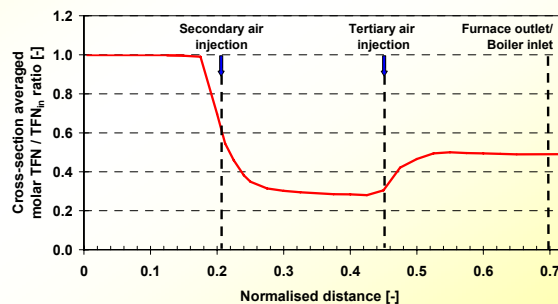
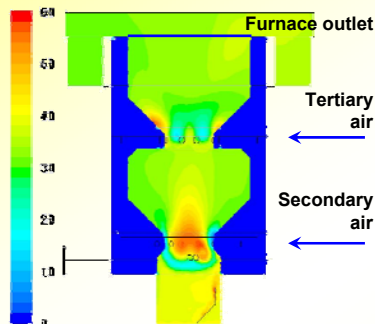
Profiles of NO and N₂ net production rate (indicator for NO_x reduction) in a biomass grate furnace and comparison measurement/simulation

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

37

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

NO [ppmv]



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

38



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Intelligent process control systems for biomass combustion plants – current status

- 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

39



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Intelligent process control systems for biomass combustion plants – alternative and new approaches

- **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

40



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Ongoing research and future R&D topics

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

41



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Thank you for your attention

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42