Combustion characteristics of Miscanthus based on lab-scale and pilot-scale combustion trials in Austria

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Presentation - overview

- Introduction and objectives
- Methodology
- Results
  - Chemical characterisation
  - General data regarding the lab-scale and pilot-scale test runs
  - NO_x emissions
  - K-release and fine PM emission formation
  - HCl and SO_2 emissions
  - Deposit formation
  - Ash melting
- Conclusions and recommendations

Introduction (I)

- Energetic biomass utilisation is a steadily growing market.
- New options of biomass resources for combustion processes are needed in order to cover the growing fuel demand.
- Short rotation crops (SRC) represent an interesting future potential.
- Miscanthus is one promising option for an economically feasible utilisation of new biomass fuels in biomass combustion plants.

Introduction (II)

- **Project in order to investigate the combustion related characteristics of new biomass fuels such a Miscanthus.**

- **Scientific partners:**

  BIOENERGY 2020+ GmbH

  Institute for Process and Particle Engineering Graz University of Technology

- **Company partners**

  BIOS BIOENERGIESYSTEME GmbH

  MAWERA Holzfeuerungsanlagen GmbH

Objectives

- **Combustion related characterisation of Miscanthus by applying a new approach for biomass fuel characterisation based on the combined evaluation of selected testing methods.**
  - Wet chemical fuel analyses and calculation of fuel indexes
  - Combustion tests in a lab-scale combustion reactor
  - Combustion trials at a pilot-scale (350 kW) grate-fired combustion plant
- **Evaluation of the results.**
- **Identification of fuel specific parameters and characteristics which are of relevance for an appropriate design and control of biomass combustion systems suitable for Miscanthus.**

Methods applied (I)

- **Miscanthus from a testing plantation in Hessen (Germany) has been used**
- **Fuel analyses**
  - **Moisture content** (drying at 105°C; CEN/TS 14774-1)
  - **Ash content** (ashing in oxidising atmosphere at 550°C; CEN/TS 14775)
  - **C, H, N** (elemental analyser; ÖNORM CEN/TS 15104)
  - **Cl** (bomb combustion in O_2 ion chromatography; ÖNORM CEN/TS 15289)
  - **Al, Ca, Fe, K, Mg, Mn, Na, P, S, Si, Zn, Pb**
    (multi-step pressurised digestion with HNO_3 / HF / H_3BO_3;
    detection with ICP-OES and ICP-MS; ÖNORM CEN/TS 12290 or 15297)
  - **GCV** (ÖNORM CEN/TS 14918)
  - **Bulk density**

Methods applied (II)

➢ Lab-scale reactor tests

- **Objectives**
  - Determination of the combustion behaviour of biomass fuels.
  - Determination of the release of gaseous compounds from the fuel during thermal decomposition.
  - First indications concerning ash melting behaviour.

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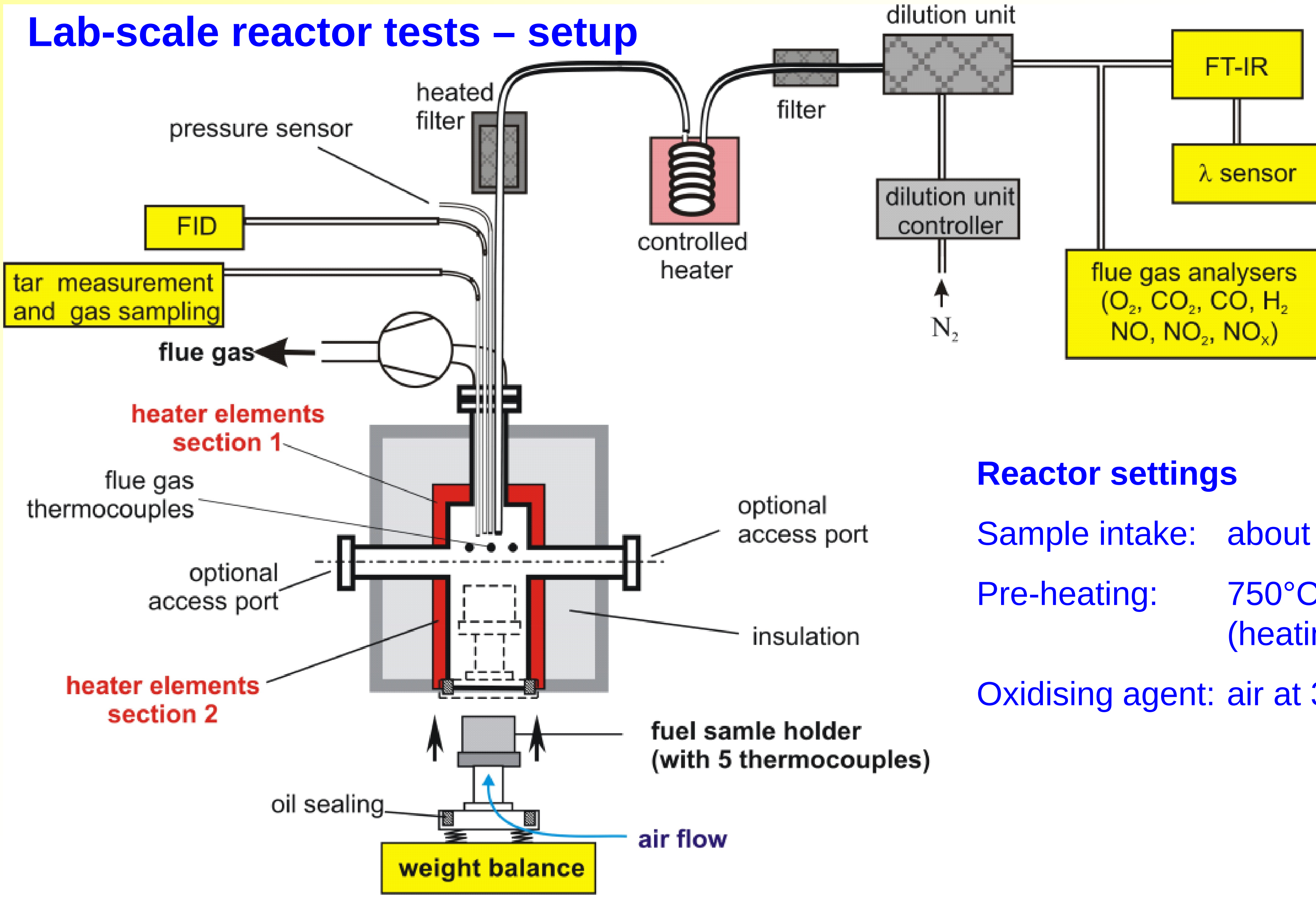
Methods applied (III)

Lab-scale reactor tests – setup



Reactor settings

Sample intake: about 85 g (wet material)

Pre-heating: 750°C / 450°C (heating element 1 / 2)

Oxidising agent: air at 30 l/min (at 20°C)

Methods applied (IV)

Pilot-scale combustion tests

- **Plant data**
  - Horizontally moving grate
  - Staged combustion
  - Flue gas recirculation below and above the grate
  - Fire-tube hot water boiler (350 kW)
- **Measurements, sampling and analyses**
  - Fuel and ash sampling with subsequent chemical analyses
  - Recording of all relevant plant operation data (temperatures, combustion air flow rates, load, etc.)
  - Gaseous emissions (O_2, CO, NO_x, HCl, SO_2)
  - Particulate emissions (PM_1, total dust)
  - Deposit probe sampling and deposit analyses (SEM/EDX)

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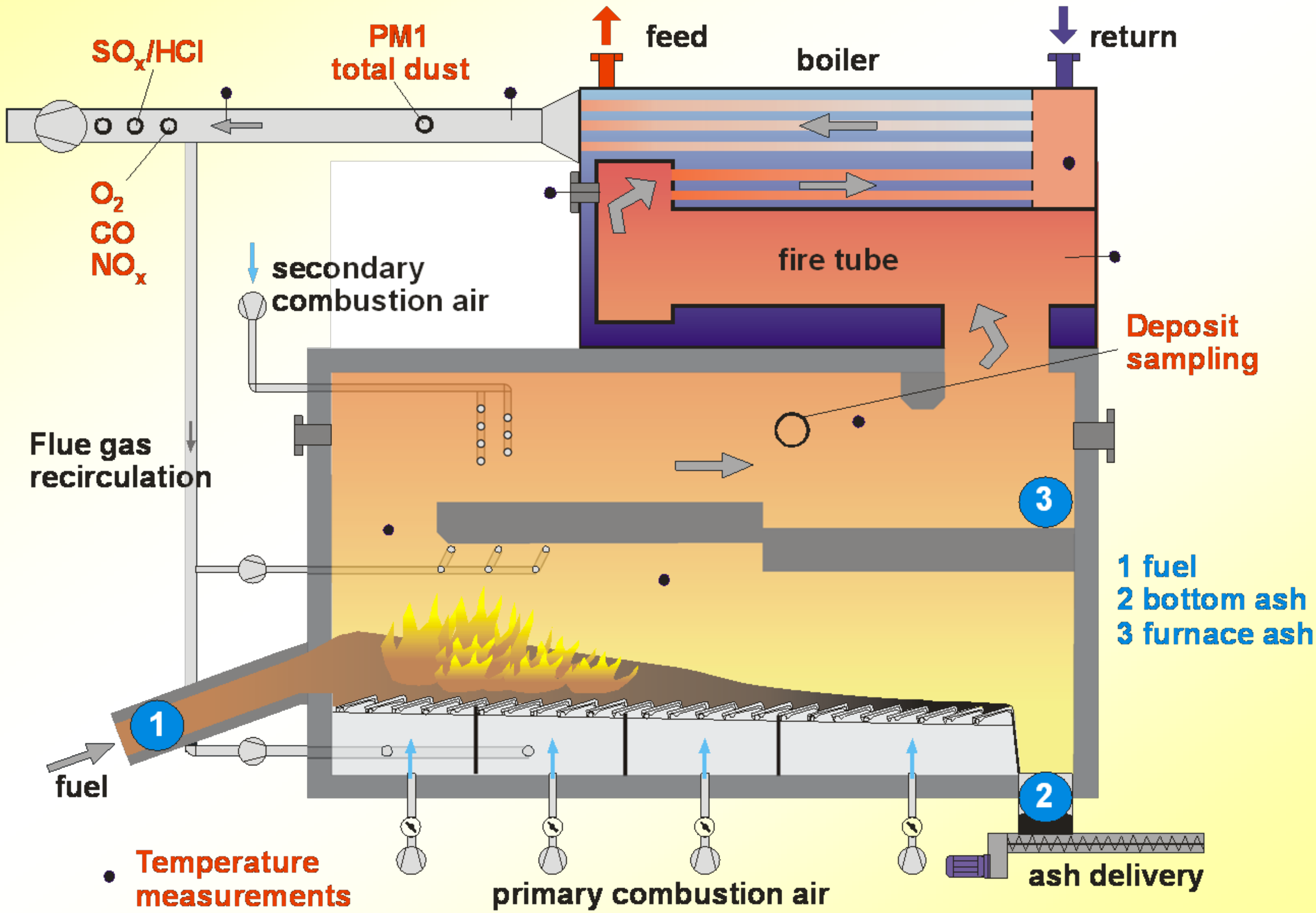
Scheme of the pilot-scale combustion plant



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Results – wet chemical analyses

		Miscanthus			Database values - Miscanthus		
		lab-scale	pilot-scale 1	pilot-scale 2	Mean	Minimum	Maximum
Moisture content	wt% w.b.	8.60	15.07	15.81			
Ash content	wt% d.b.	2.62	2.40	2.52	4.39	2.04	14.53
Carbon (C)	wt% d.b.	47.32	48.21	48.34	48.21	46.70	50.70
Hydrogen (H)	wt% d.b.	6.06	5.92	5.90	5.43	4.40	5.78
Nitrogen (N)	wt% d.b.	0.37	0.34	0.38	0.38	0.04	1.70
Sulphur (S)	mg/kg d.b.	547	561	598	573	200	1,800
Chlorine (Cl)	mg/kg d.b.	1,390	1,420	1,430	2,106	700	3,800
Silica (Si)	mg/kg d.b.	2,210	2,260	2,560	20,537	6,930	34,963
Calcium (Ca)	mg/kg d.b.	1,010	728	787	4,667	800	10,724
Magnesia (Mg)	mg/kg d.b.	534	534	599	1,659	400	4,501
Phosphorus (P)	mg/kg d.b.	921	1,010	1,040	625	427	750
Potassium (K)	mg/kg d.b.	8,550	8,940	9,130	5,293	1,500	12,250
Sodium (Na)	mg/kg d.b.	53.0	50.3	68.1	335.9	17.0	1,197
Zinc (Zn)	mg/kg d.b.	19.00	14.40	15.60	16.19	11.07	21.00
Lead (Pb)	mg/kg d.b.	0.46	< 5	< 5	2.31	0.12	10.91
Si/K	mole/mole	0.36	0.35	0.39	5.40		
2S/Cl	mole/mole	0.87	0.87	0.92	0.60		
(K+Na) / (2S+Cl)	mole/mole	3.01	3.08	3.05	1.58		
K+Na+Zn+Pb	mg/kg d.b.	8,622	9,009	9,218	5,647		
Gross calorific value (GCV)	MJ/kg d.b.	19.30	18.83	19.09	19.11	17.80	19.51
Net calorific value (NCV)	MJ/kg w.b.	15.78	14.91	14.81			
Bulk density (chipped material)	kg/m³	n.d.	98.6	99.4			
Energy density	kWh/m³	n.d.	408.7	408.8			

w.b. ... wet basis; d.b. ... dry basis; n.d. ... not determined

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Results from wet chemical analyses – relevant fuel indexes

- **Si/K: 0.35 – 0.39 mole/mole**
  - Considerably lower than the database mean value, even lower than for wood fuels
  - → moderate embedding of K in the bottom ashes by the formation of K-silicates can be expected

- **2S/Cl: 0.87 – 0.92 mole/mole**
  - 2S/Cl < 1
  - → problems with corrosion have to be expected when high superheater temperatures are applied

- **(K+Na)/(2S+Cl): 3.01 – 3.08 mole/mole**
  - (K+Na)/(2S+Cl) >>1: due to the alkaline surplus a good embedding of S and Cl into the ashes should take place
  - → only minor SO_2 and HCl emissions are expected

- **K+Na+Zn+Pb: 8,622 – 9,219 mg/kg (d.b.)**
  - contribute to the formation of fine particulates
  - → due to the very high value high fine PM emissions as well as high deposit build-up rates on heat exchanger tubes and cooled walls are expected

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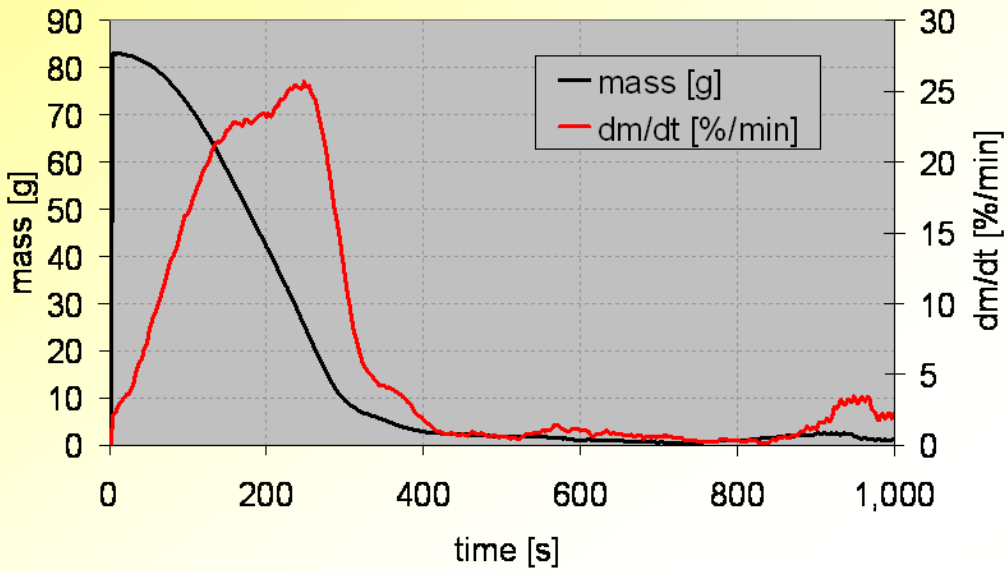
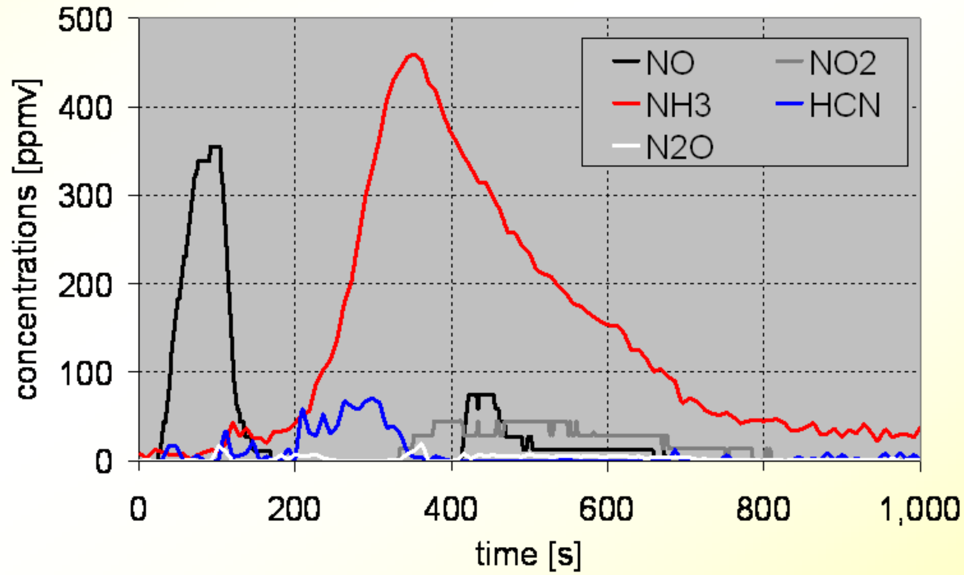
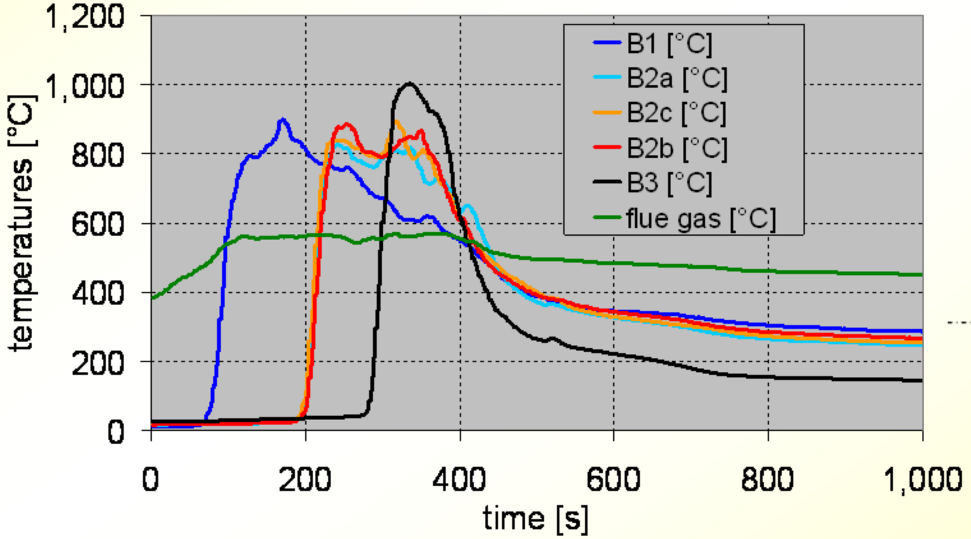
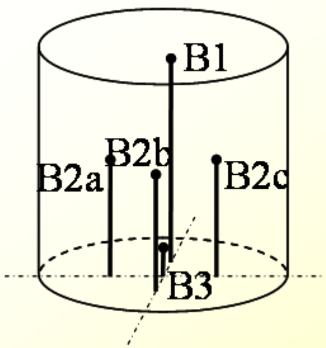
Lab-scale reactor tests – results (example from one test run)









Explanations:

sample mass: 84.7 g (wet material)

moisture content: 8.6 wt% (w.b.)

Pilot-scale test runs – general data

- **23 hours test run performed**
  - By flue gas recirculation the combustion temperatures should be kept low (<950°C in the primary combustion zone) in order to reduce/avoid slagging problems

- **Air staging and flue gas recirculation data**
  - flue gas recirculation ratio below grate: 0.15
    (recirculation ratio = recirculated flue gas / total flue gas)
  - flue recirculation ratio total: 0.29
  - primary combustion air ratio, λ_{prim}: 0.58
  - total excess air ratio, λ_{total}: 1.76

→ Good air staging conditions could be achieved

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Pilot-scale test runs – operation data and average emissions

duration	[h]	23.0
boiler load	[kW]	225.9
feed temperature	[°C]	72.4
return temperature	[°C]	65.0
flue gas temperature downstream boiler	[°C]	222.8
temperature of recirculated flue gas	[°C]	189.2
temperature primary combustion zone	[°C]	917.5
temperature secondary combustion zone	[°C]	1,089.9
O2 (dry flue gas)	[vol%]	9.0
CO (dry flue gas, 13 vol% O2)	[mg/Nm³]	153.9
OGC (dry flue gas, 13 vol% O2)	[mg/Nm³]	<2.0
NOx (dry flue gas, 13 vol% O2)	[mg/Nm³]	224.7

Only 65% of the nominal load could be achieved. Main reasons:

- restrictions regarding the fuel feeding system (low energy density of Miscanthus)
- a larger grate surface would have been needed to achieve an almost complete burnout at full load

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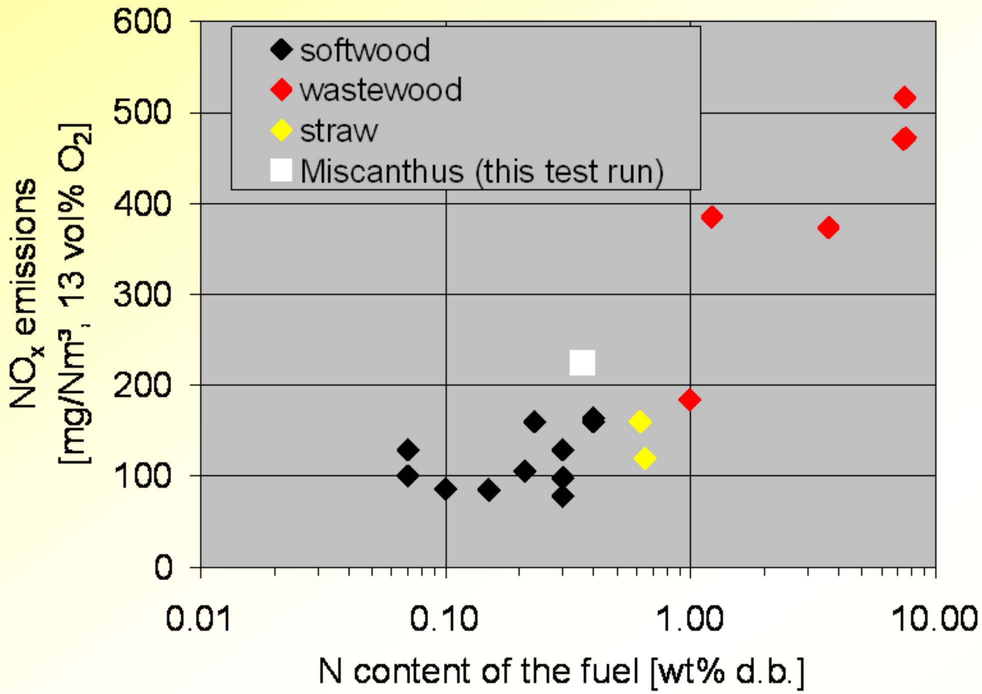
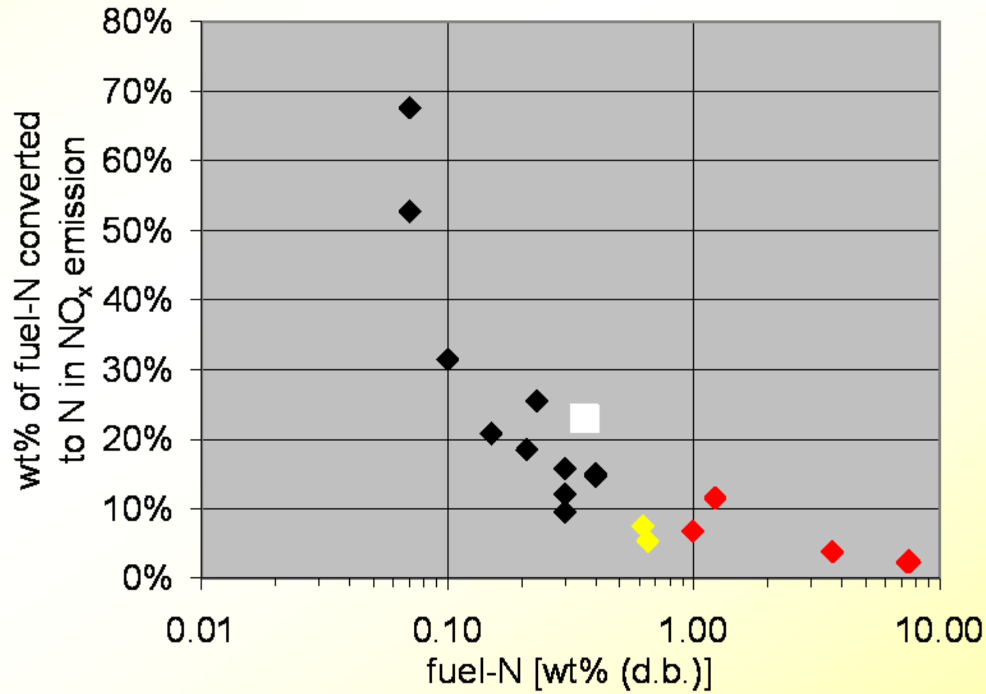
Pilot-scale test runs – NO_x-emissions





- **N content of the fuel: 0.34 to 0.38 wt% (d.b.) → increased NO_x emissions compared with chemically untreated wood fuels were expected.**
- **The conversion of fuel-N into NO_x emissions determined during the pilot-scale combustion test runs is somewhat higher than for wood fuels and straw.**

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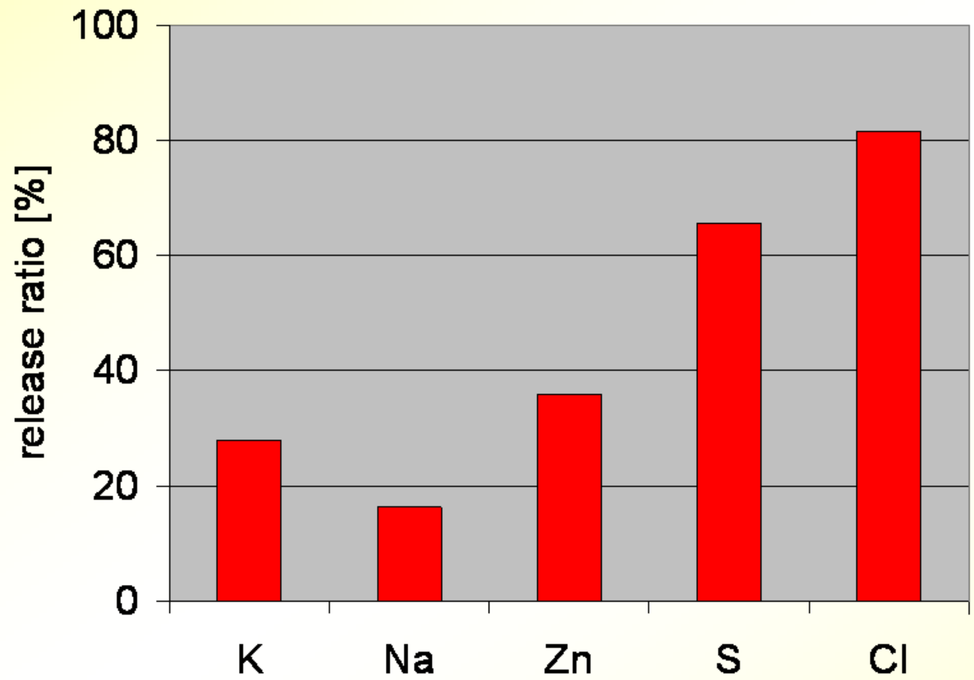
Lab-scale reactor test runs – element release as well as potential for aerosol formation



Explanations:

Release ratio [%] =

(1 – mass of element in the combustion residues / mass of element in the fuel)*100

- **From these release data a potential for aerosol formation from inorganic easily volatile species of 211 mg/Nm³ (dry flue gas, 13 vol% O_2) can be calculated.**

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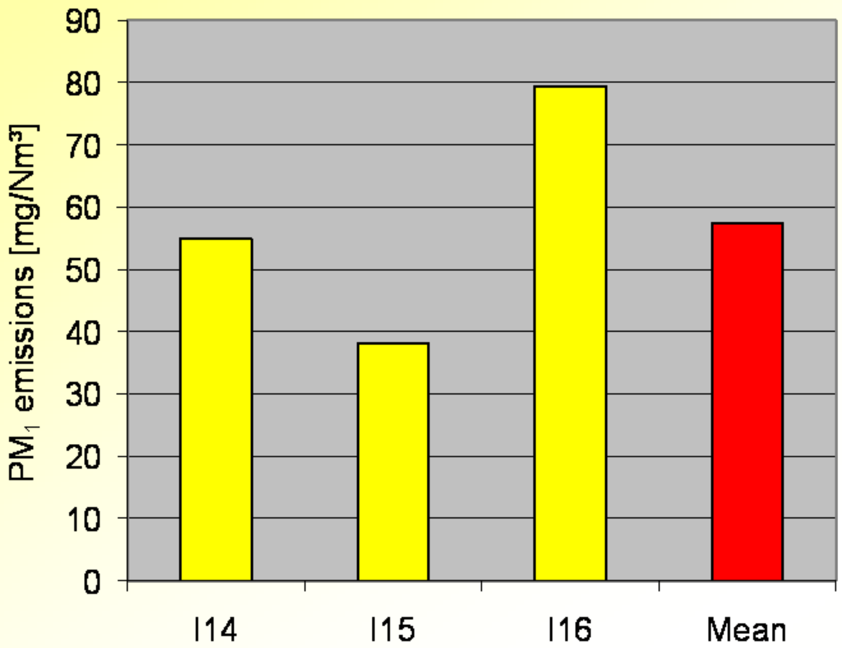
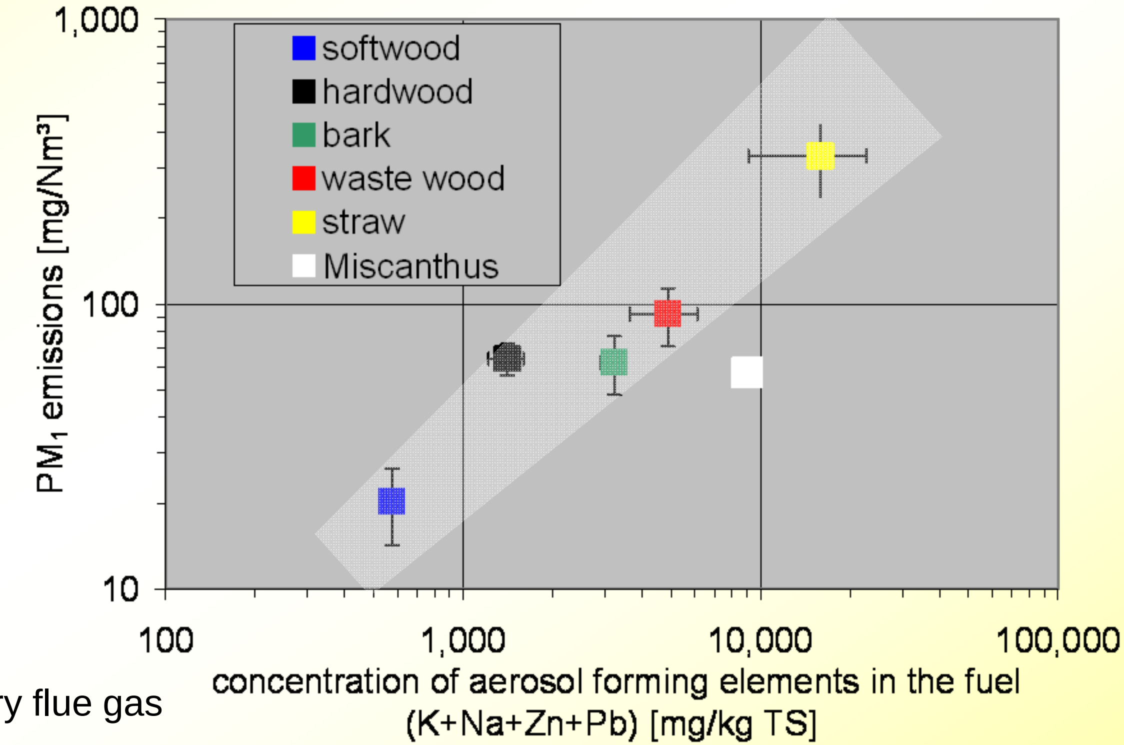
Pilot-scale test runs – aerosol (PM_1) emissions

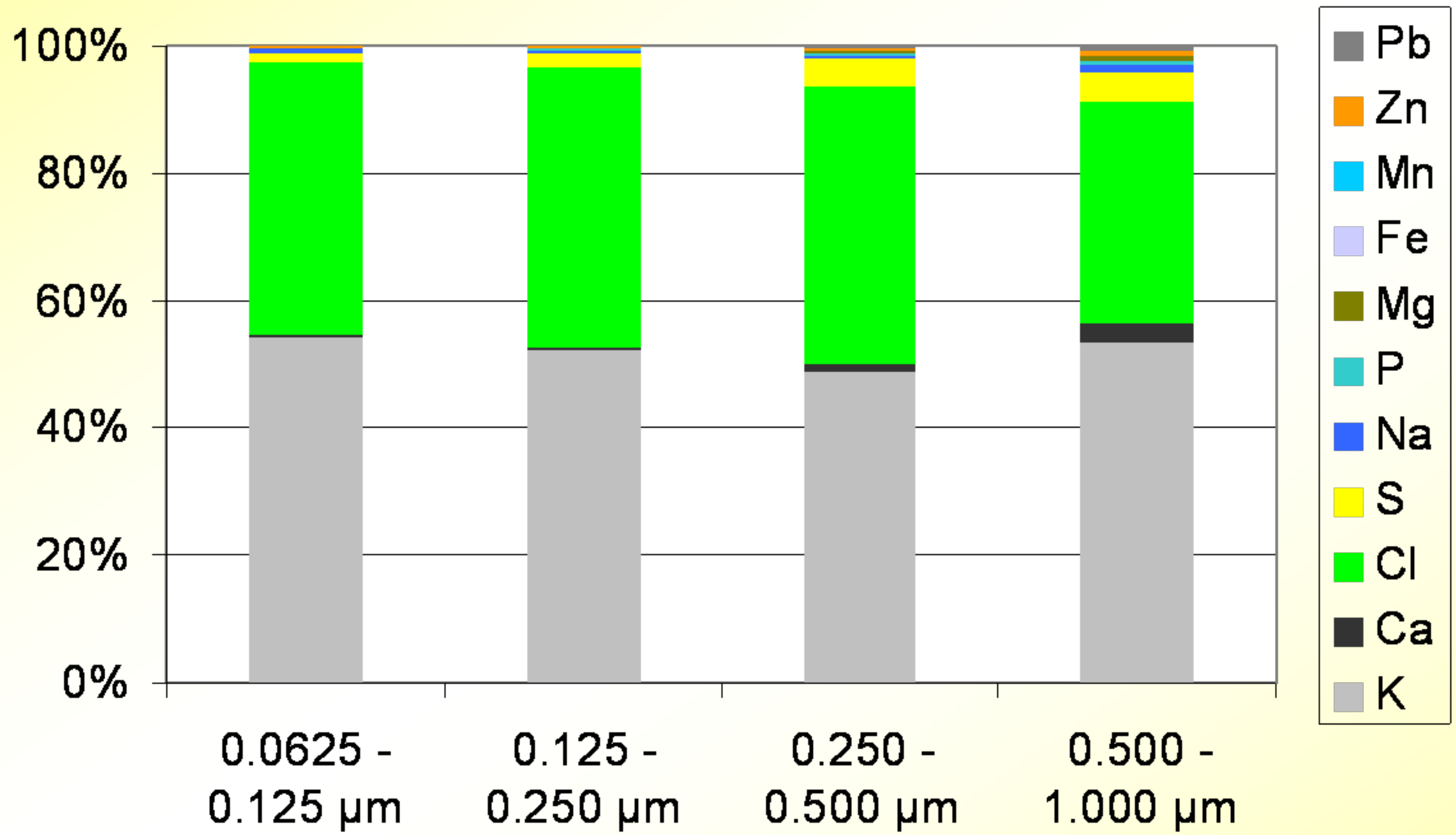




Explanations: mg/Nm³ related to 13 vol% O_2 and dry flue gas

- **Average PM_1 emissions at boiler outlet: 57.5 mg/Nm³**
- **Lower K-release than determined for other biomass fuels due to reactions of K with Si (results from element balances show that 83% of the K are embedded in the bottom ash)**
- **Lower PM_1 emissions than expected from the lab-scale reactor test runs due to the flue gas recirculation and deposit formation in the plant.**

Pilot-scale test runs – chemical composition of PM_1 emissions at boiler outlet



Explanations: results of wet chemical analyses of 4 impactor stages of one impactor measurement
results in wt% without considering oxygen

- **The fuel index 2S/Cl (0.87-0.92) also indicates preferred KCl formation.**

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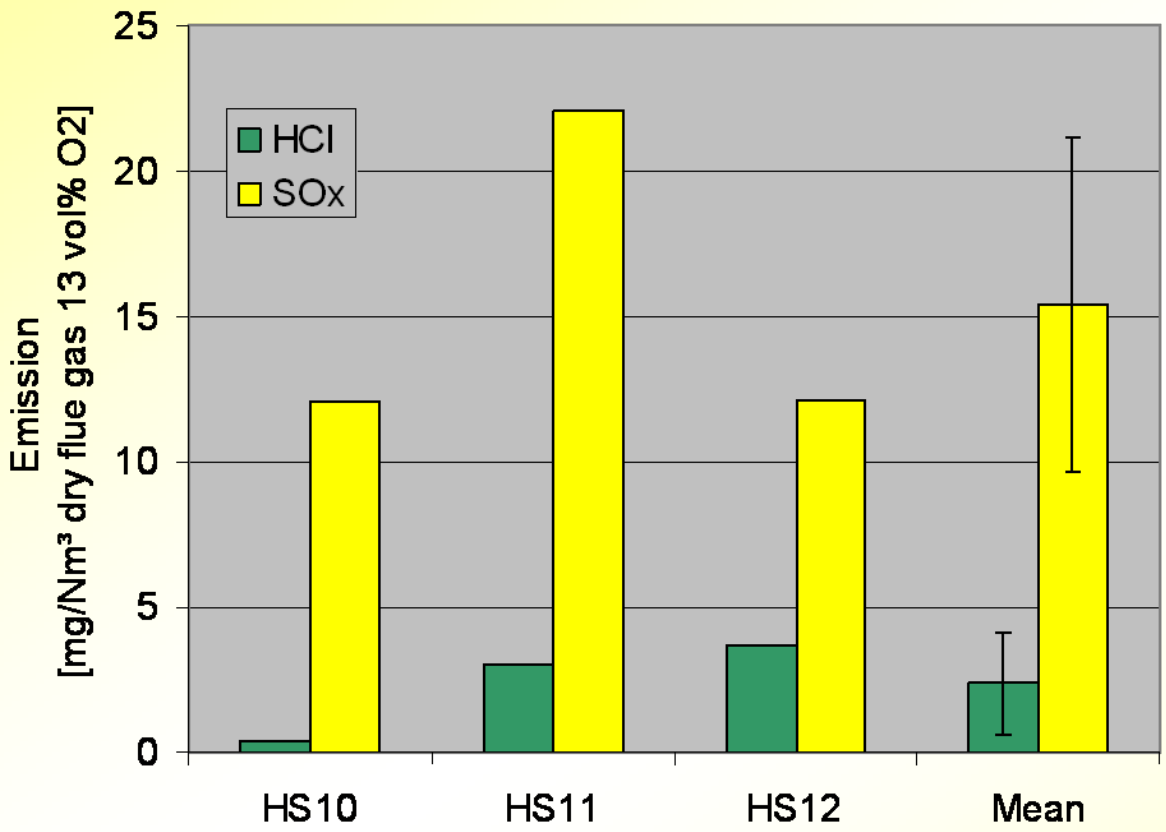
Pilot-scale test runs – HCl- and SO_x-emissions



Average emissions:

- HCl: 2.4 mg/Nm³
- SO_x: 15.4 mg/Nm³

Good embedding of Cl and S in the ashes. Element balances over the combustion plant have shown that

- 96% of the Cl and
- 62% of the S

are embedded in the ashes

The result of the emission measurements respectively the experimentally determined embedding of S and Cl in the ashes is in good agreement with the prediction made based on the evaluation of the fuel index (K+Na)/(2S+Cl)

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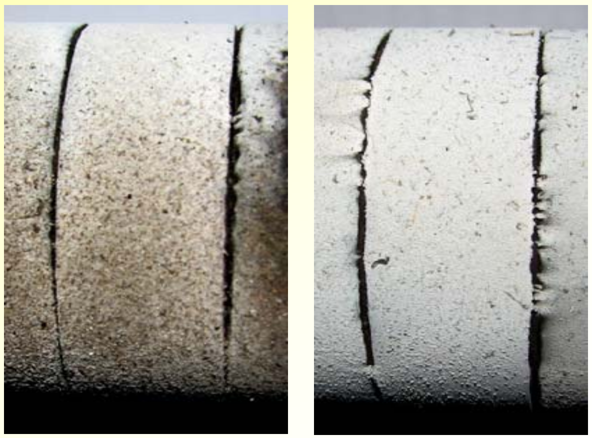
Pilot-scale test runs – deposit sampling, pictures of the probes

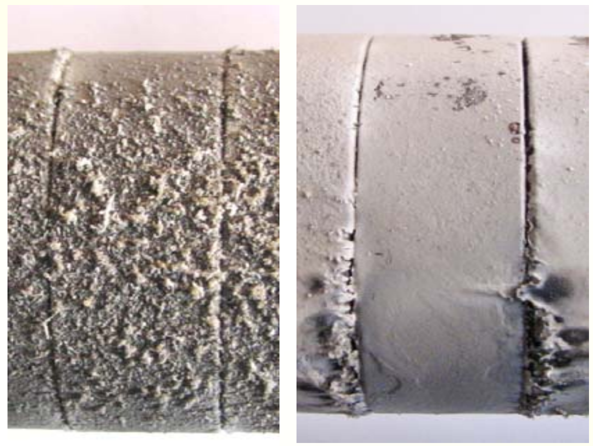
2 hours sampling time
340°C surface temperature

LUV **LEE**



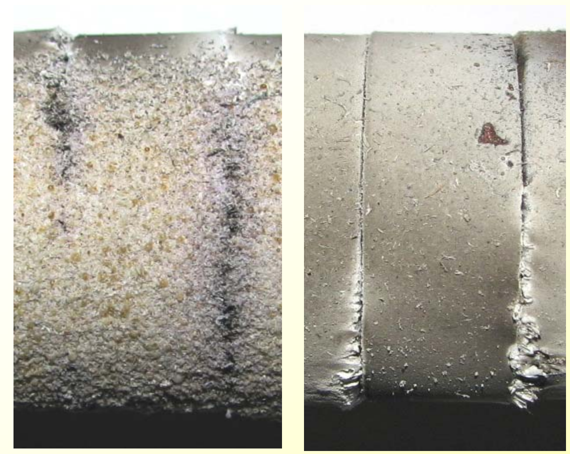
6 hours sampling time
340°C surface temperature

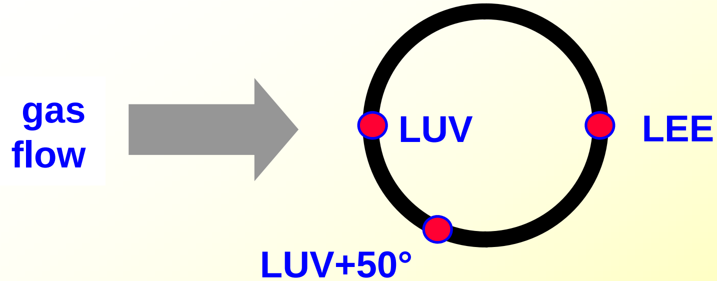
LUV **LEE**



12 hours sampling time
340°C surface temperature

LUV **LEE**

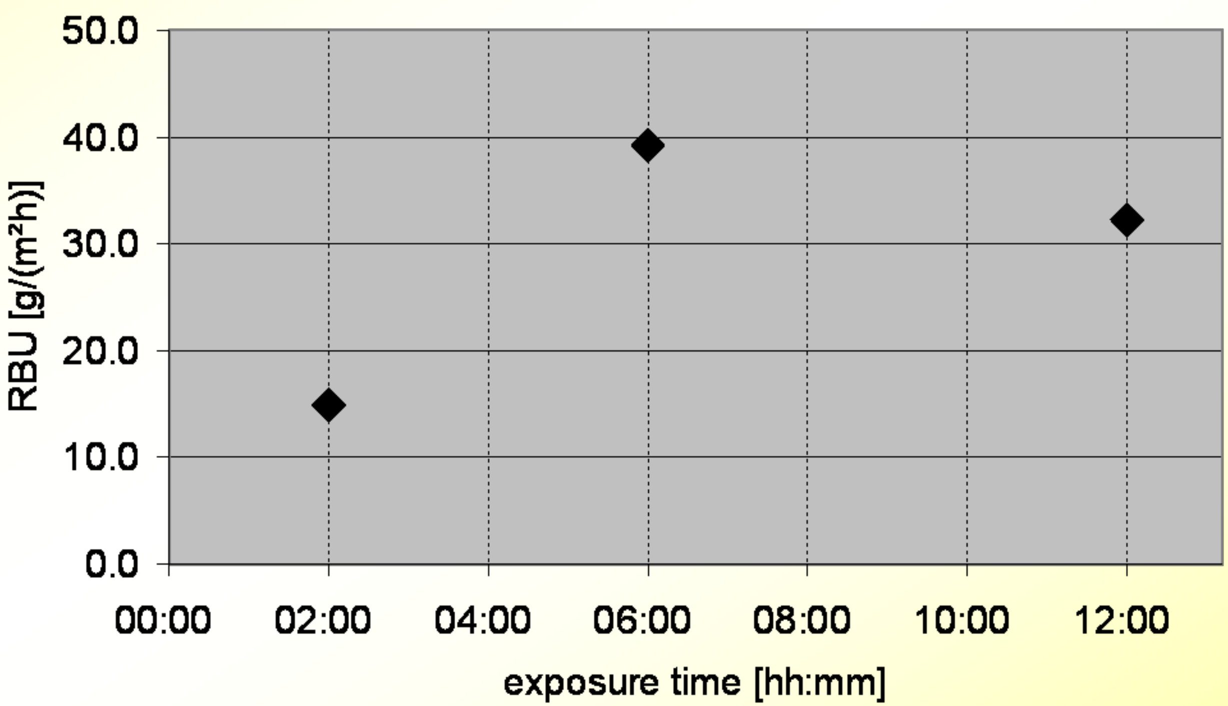




Pilot-scale test runs – RBU – rates of deposit build up

- **Decreasing RBU from 6 to 12 hours exposure time due to shedding effects**
- **RBU: 15.0 to 39.1 g/m²/h**

results from test runs at the same plant (for comparison)
chemically untreated wood chips: RBU: 1.6 to 8.3 g/m²/h
bark: RBU: 5.5 to 10.1 g/m²/h



exposure time	average flue gas temperature
2h	967°C
6h	1,027°C
12h	996°C

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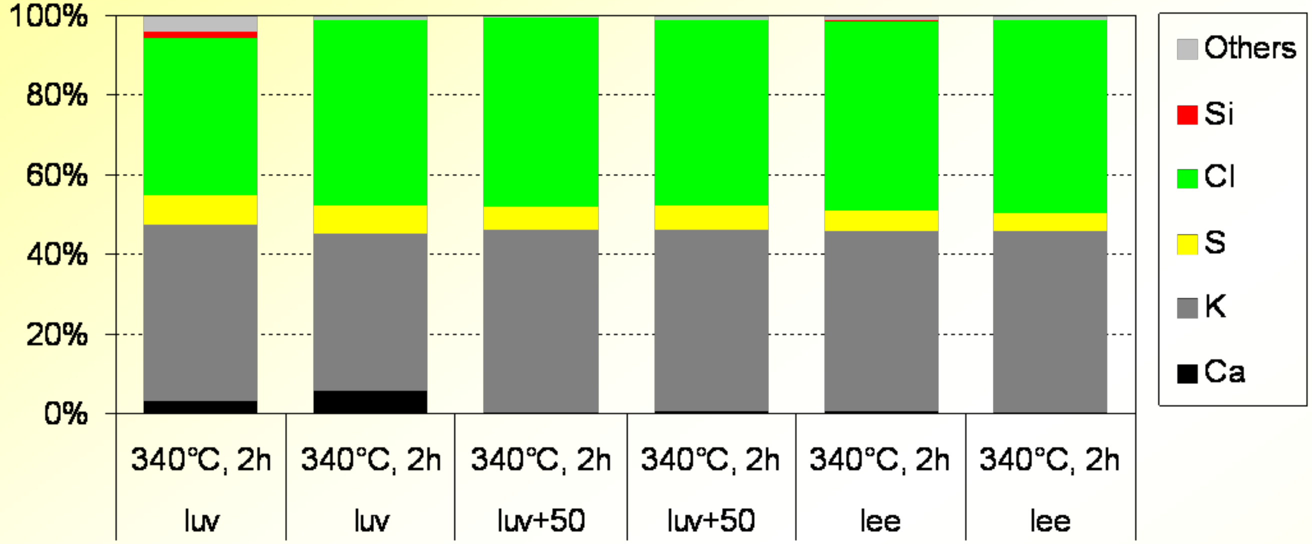
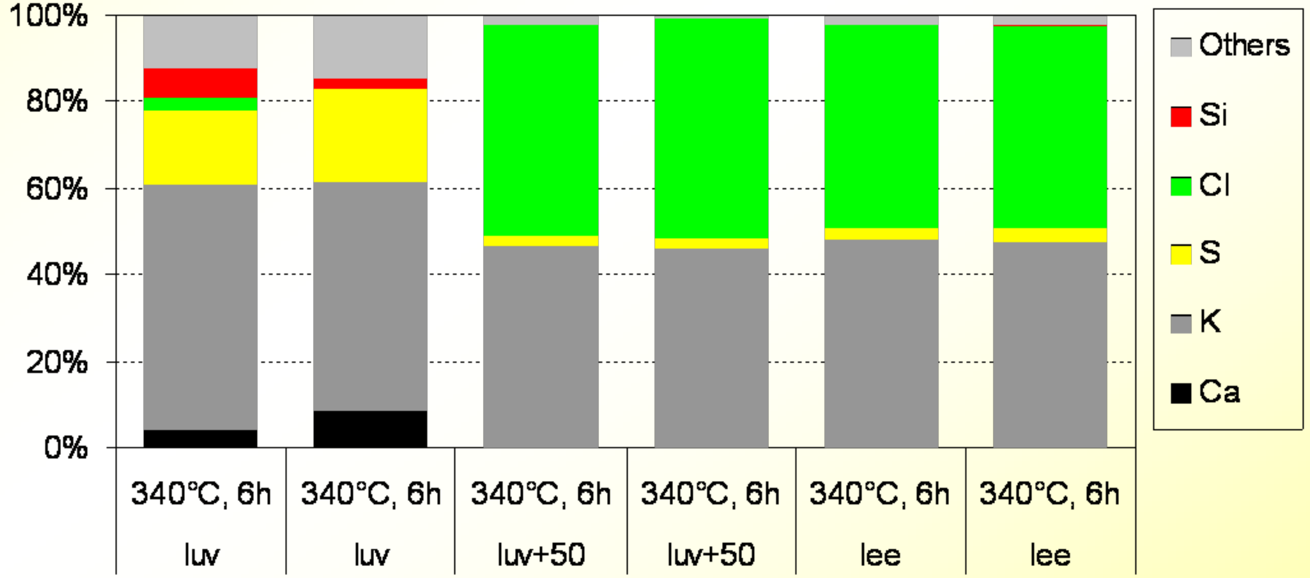
Pilot-scale test runs – chemical compositions of deposits





Deposits are strongly dominated by KCl
➔ high corrosion risk

Increasing deposition of coarse particles on the LUV side with increasing exposure time

On the LUV-side of the 6 hours sample most probably sulphation reactions have already started

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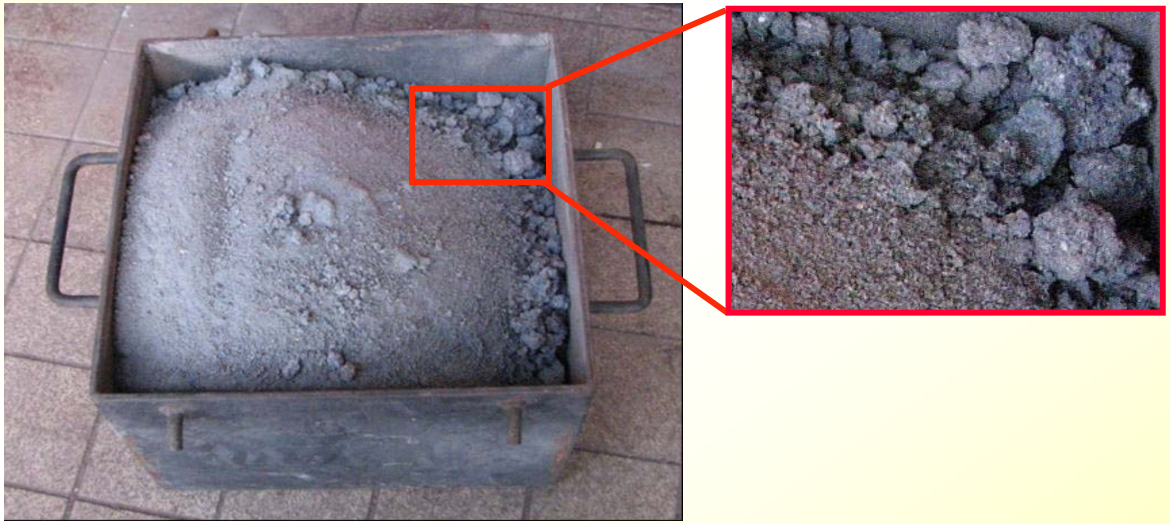
Slagging tendencies (I) – photos from the lab-scale and the pilot-scale test runs



Lab-scale reactor:

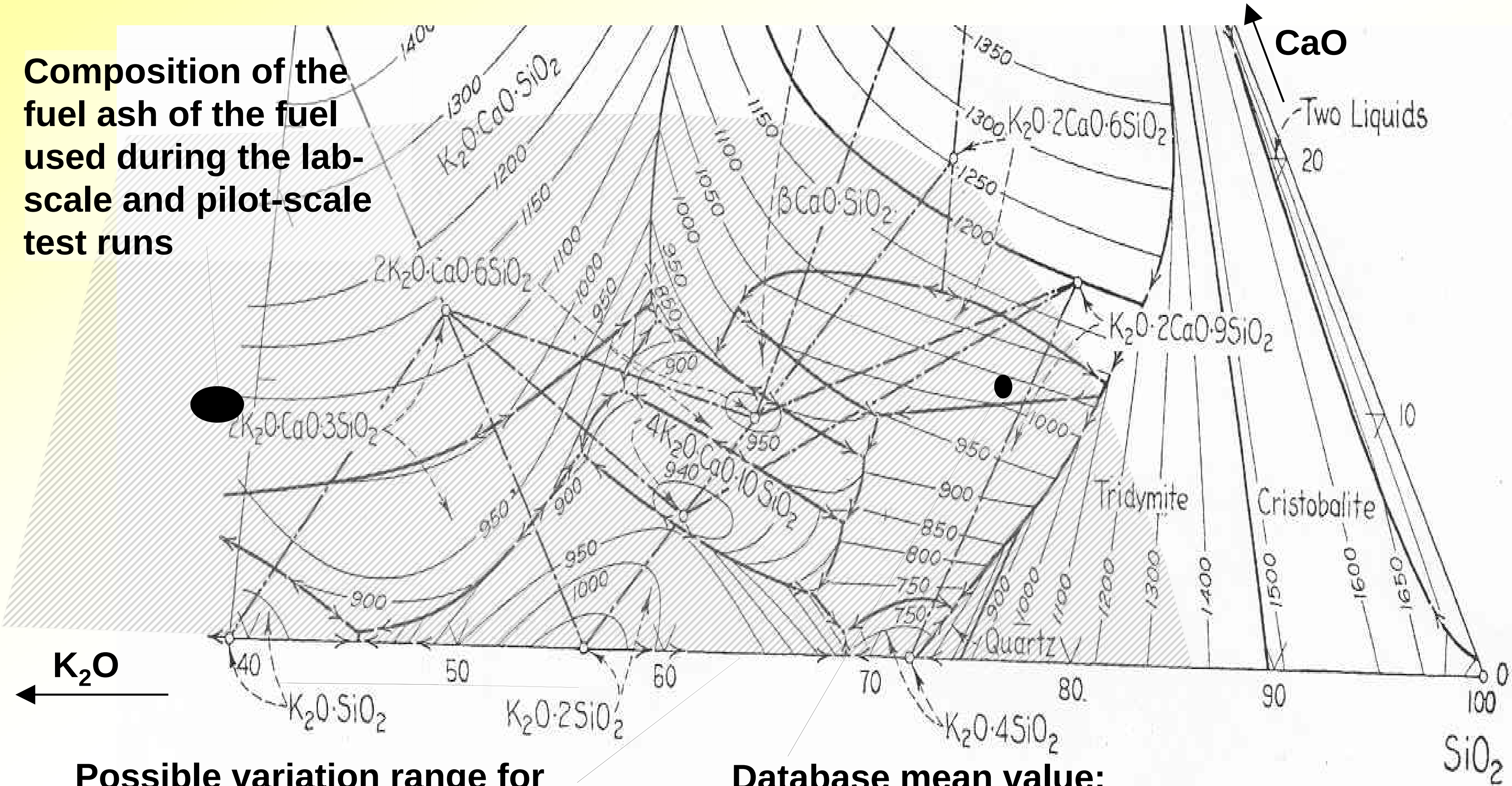
- some ash sintering occurred

Pilot-scale test run:

- small slag pieces in the grate ash
- no ash melting in the secondary combustion zone

Slagging tendencies (II)

Composition of the fuel ash of the fuel used during the lab-scale and pilot-scale test runs



Possible variation range for Miscanthus fuel ash compositions

Database mean value: fuel ash composition

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Conclusions and recommendations (I)

- **A novel advanced fuel characterisation method based on the combination of**
  - wet chemical analyses (including the evaluation of defined fuel indexes)
  - lab-scale reactor tests and
  - pilot-scale combustion test

  has successfully been applied.

- **The results gained from the three methods supplement each other regarding the evaluation of combustion relevant fuel characteristics and provide a good picture of the fuel behaviour to be expected during Miscanthus combustion.**

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Conclusions and recommendations (II)

- **With the fuel feeding system and the grate system applied only 65% of the nominal load could be reached.**

  → **The low energy density of loose Miscanthus has to be considered during the design of the fuel feeding system.**

  → **For Miscanthus combustion the specific grate surface load (kW/m²) has to be reduced.**
  The lab-scale reactor tests indicated a, compared with wood fuels, slower charcoal combustion and the pilot-scale tests have shown, that even at 65% load almost the whole length of the grate was needed to achieve acceptable burnout.

- **A good gas phase burnout (average CO emissions of 154 mg/Nm³ and OGC emissions <2 mg/Nm³ related to dry flue gas and 13 vol% O_2) could be achieved.**

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Conclusions and recommendations (III)

- Even if a good air staging with a low primary air ratio (0.58) was applied, a compared with wood and straw combustion, increased transformation of fuel N into NO_x emissions was determined (average NO_x emission: 225 mg/Nm³).
  → utilisation of the potential of primary measures for NO_x emission reduction and, depending on the emission limit, maybe also secondary measures for NO_x emission control are necessary

- Although Miscanthus is a K-rich fuel, moderate PM_1 emissions of 58 mg/Nm³ (related to dry flue gas and 13 vol% O_2) have been determined at boiler outlet.
  → good embedding of K in the bottom ash by appropriate fuel bed cooling (air staging and flue gas recirculation)

  The results of the lab-scale reactor tests indicate a potential for aerosol formation of about 210 mg/Nm³. The difference compared with the PM_1 emissions measured is mainly related to the formation of KCl-rich deposits (as confirmed by the deposit probe measurements) as well as to the lower fuel bed temperatures at the pilot-scale plant (due to air staging and flue gas recirculation).

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Conclusions and recommendations (IV)

- **Significantly increased deposit build-up rates have been determined (up to 39 g/m²/h)** (4 to 20 times higher than those for wood chip and bark combustion determined at the same plant)
  → an efficient boiler cleaning system is needed for Miscanthus combustion

- **Deposits mainly consist of KCl. Between 6 and 12 hours exposure time of the deposit probe sulphation reactions occurred.**
  → a high risk for boiler tube corrosion at high surface temperatures exists which has to be considered concerning superheater design and cleaning

- **Only minor slag formation on the grate could be observed which was mainly due to the fact that the furnace temperatures were kept on a low level by flue gas recirculation and air staging. However, broad variations concerning Si and K contents of Miscanthus are possible and therefore fuel ash compositions with significantly lower ash melting temperatures could result.**
  → an appropriate furnace cooling (primary combustion zone <950°C) is recommended to avoid excessive ash melting (can be achieved by a combination of air staging and flue gas recirculation)

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