Co-combustion of waste with coal in fluidized bed systems - an overview

Joachim Werther
Technical University Hamburg-Harburg
D 21071 Hamburg, Germany

Definition and Scope

What is waste?

‘Waste’ means any substance or object which the holder disposes of or is required to dispose of pursuant to the provisions of national law in force

Waste considered in the context of co-combustion with coal in power power plant:

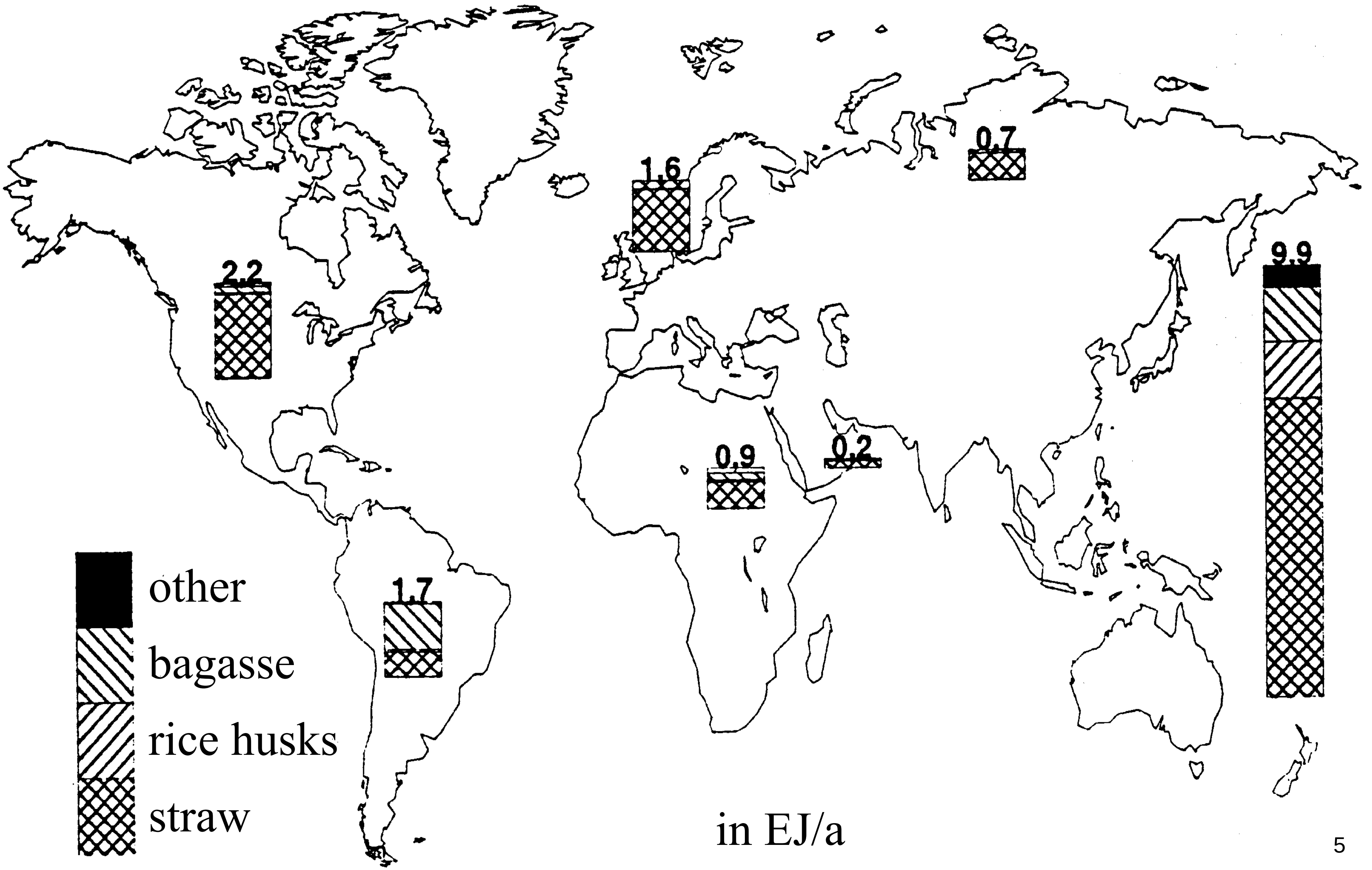
- waste wood → biomass
- agricultural residues → biomass
- sewage sludge

CONTENTS

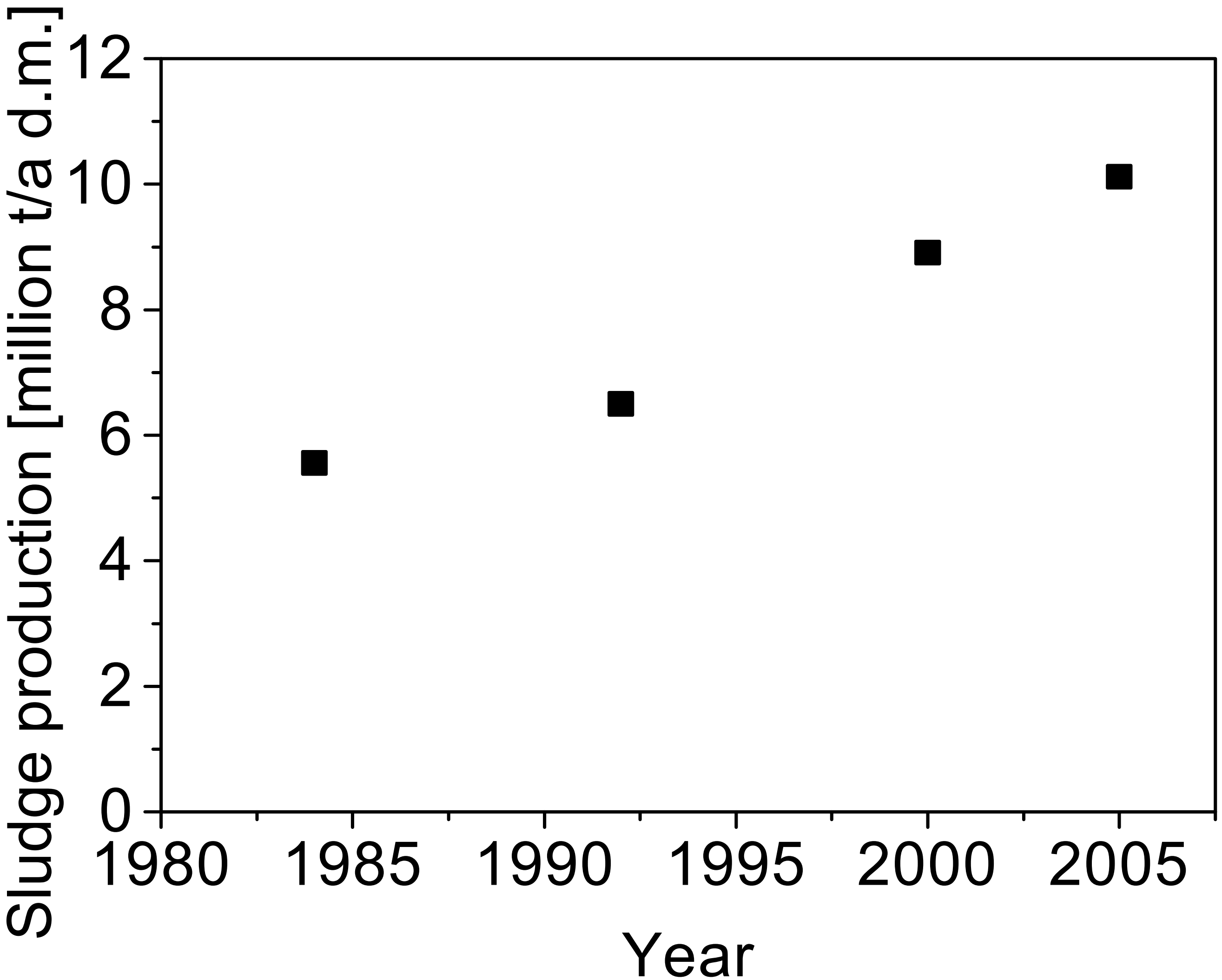
Motivation for utilization of waste for power generation

- 1. Energy Potential
  - Wood wastes and residues: 41.6 EJ/a
  - Agricultural residues: 17.2 EJ/a
  - Incentives for use of renewable energies
- 2. Kyoto Protocol
  - Overall reduction of GHG by 5 %
  - European Union committed to 8 % reduction
- 3. Sewage sludge
  - Land filling to decrease (e.g. TASi)
  - Incineration to increase
- 4. Governmental actions
  - Germany has decided to step out of nuclear energy
  - ‘Renewable energy law’ promises subsidies (0.1 €/kWh)
  - In Denmark: 1 million tons/year straw to be used for power generation

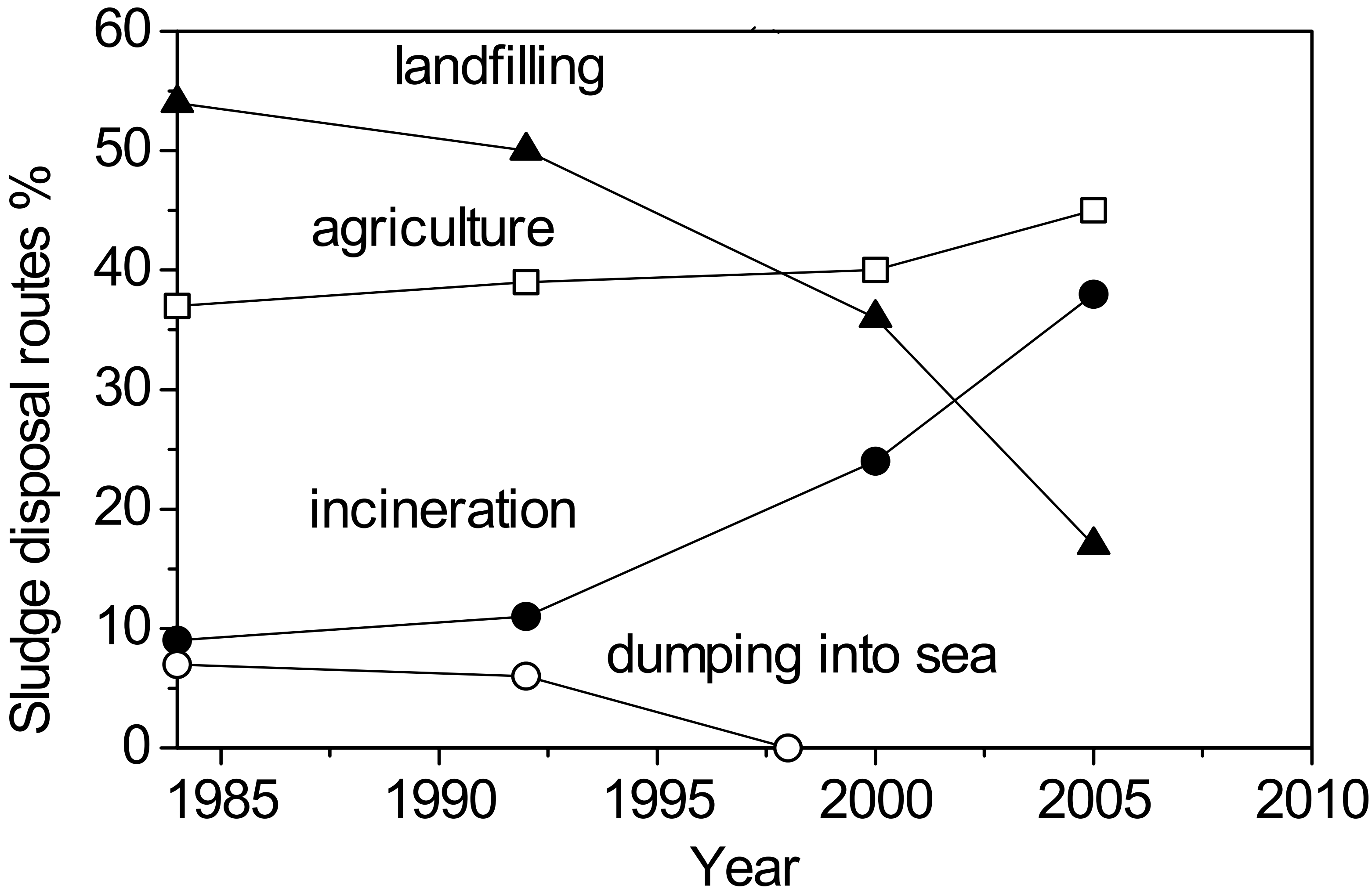
Energy potential of agricultural residues



Estimation of sewage sludge production in EU



Sludge disposal routes in the EU



Advantages of co-firing waste with coal

- Capitalize on economy of scale
- Useful within economic transport distance of 50-80 km
- Caters well for seasonality of biomass production
- High volatile matter of biomass compensates high carbon content of coal
- Low cost CO_2 reduction technique
- Low SO_2 emission credits
- Coal furnaces improve the efficiency of biomass combustion
- Coal furnaces have efficient flue gas cleaning
- A reliable short term disposal opportunity for wastes

Problems with utilization of waste as fuels

1. For agricultural residues:
   - local production + low density ⟶ high transport costs
   - annual harvest requires large storage space
   - storage is associated with loss of biological substance and bears risk of self ignition
   - low energy density requires larger plant size ⟶ higher investment costs than fossil -fired plants

2. For agricultural residues and sewage sludges:
   - wide variety of fuel characteristics
   - high volatile content
   - risk of slagging, fouling, corrosion and agglomeration

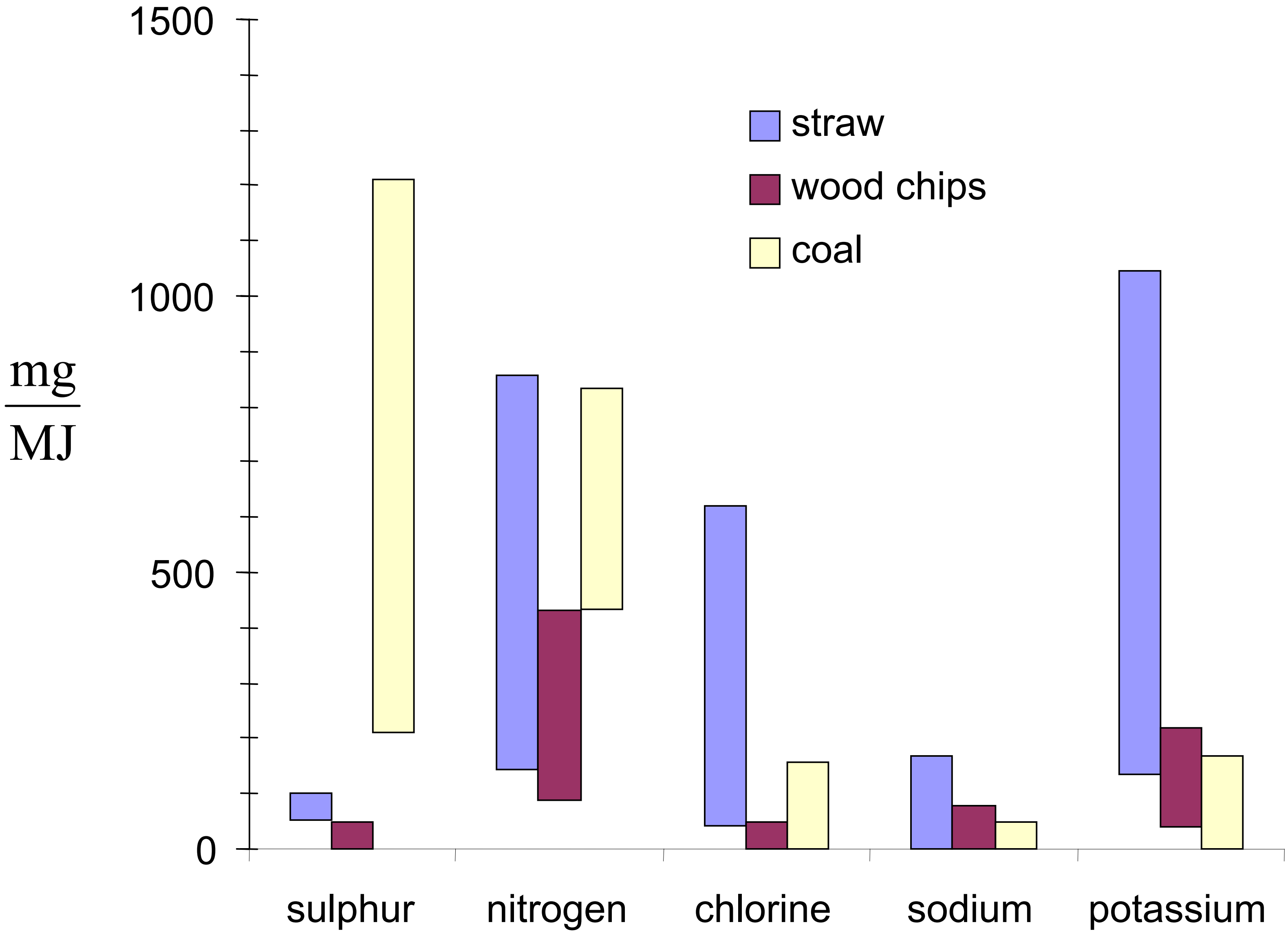
Fuel characteristics

	proximate analysis				ultimate analysis (%waf)				
	moisture (%raw)	volatiles (%waf)	fixed C (%waf)	ash (%wf)	C	H	O	N	S
road side grass	16	61.7	38.3	23.1	48.2	6.6	41.9	1.94	0.24
wheat straw	20	77.0	23.0	5.7	48.4	6.2	45.0	0.58	0.09
soy husk	6.3	78.6	21.4	5.4	45.4	6.7	46.9	0.9	0.1
coffee husk (mbuni)	11.4	76.4	23.7	4.6	43.9	4.8	49.6	1.6	0.1
coconut shell	4.4	76.2	23.8	3.2	51.2	5.6	43.1	0.0	0.1
sewage sludge	6.9	86.4	13.6	44.6	52	6.3	32.1	6.3	3.1
wood	40.0	84.9	23.3	0.8	50.7	5.9	43.1	0.2	0.04
peat	37.0	69.8	30.2	6.8	57.1	5.9	43.1	2.3	0.8
bituminous coal	7.5	38.8	61.2	5.3	88.0	6.0	4.0	1.2	0.8

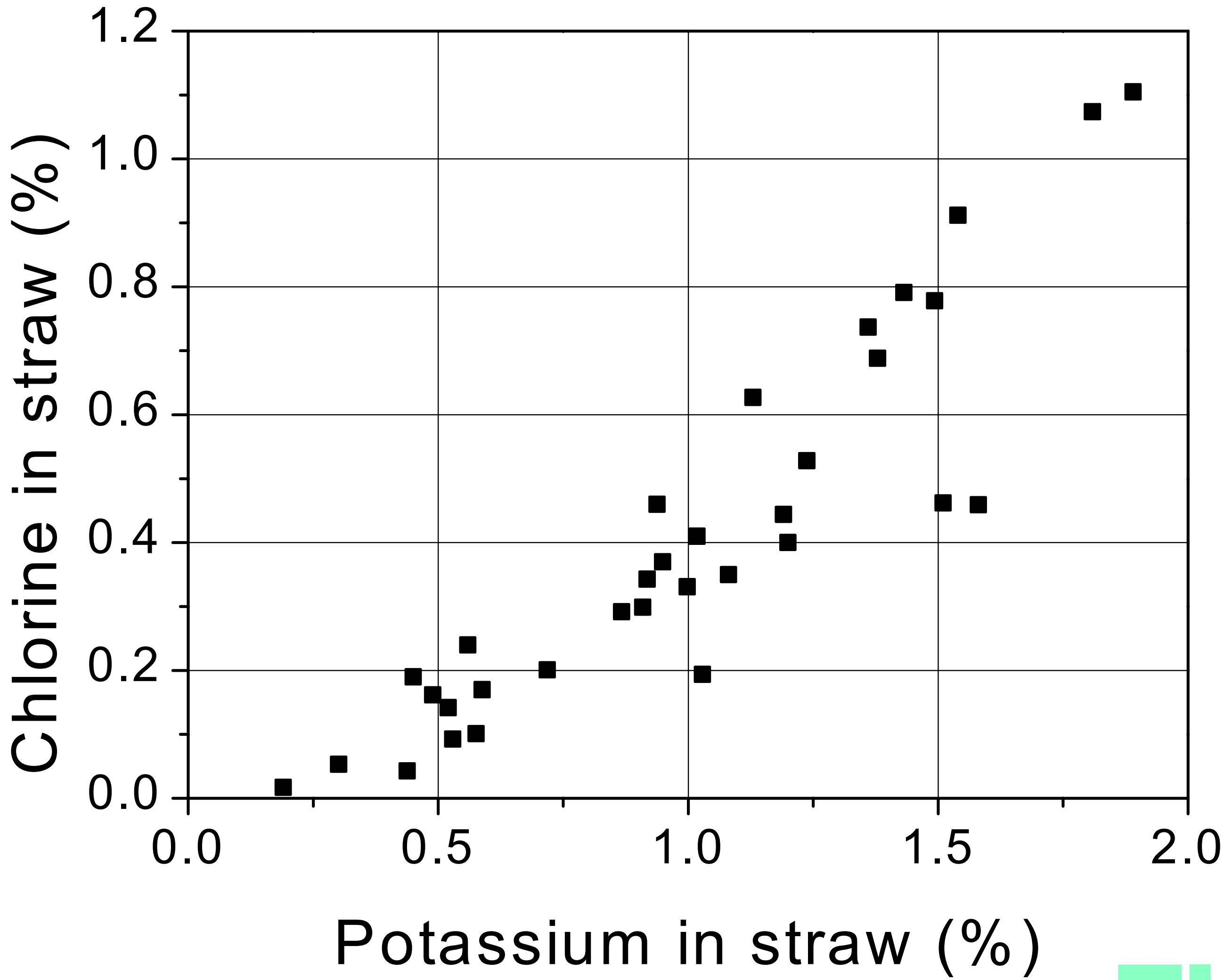
Characteristics of agricultural residues used as fuels

- moisture content depends on processing (coffee beans are dried before hulling, straw quality depends on weather conditions at time of harvesting)
- volatiles content is significantly higher than in coals
- ash content is low
- oxygen content is high
- low sulfur content but high contents of chlorine (→ HCl emissions, dioxin formation, corrosion), sodium and potassium (→ ash melting behavior, agglomeration)

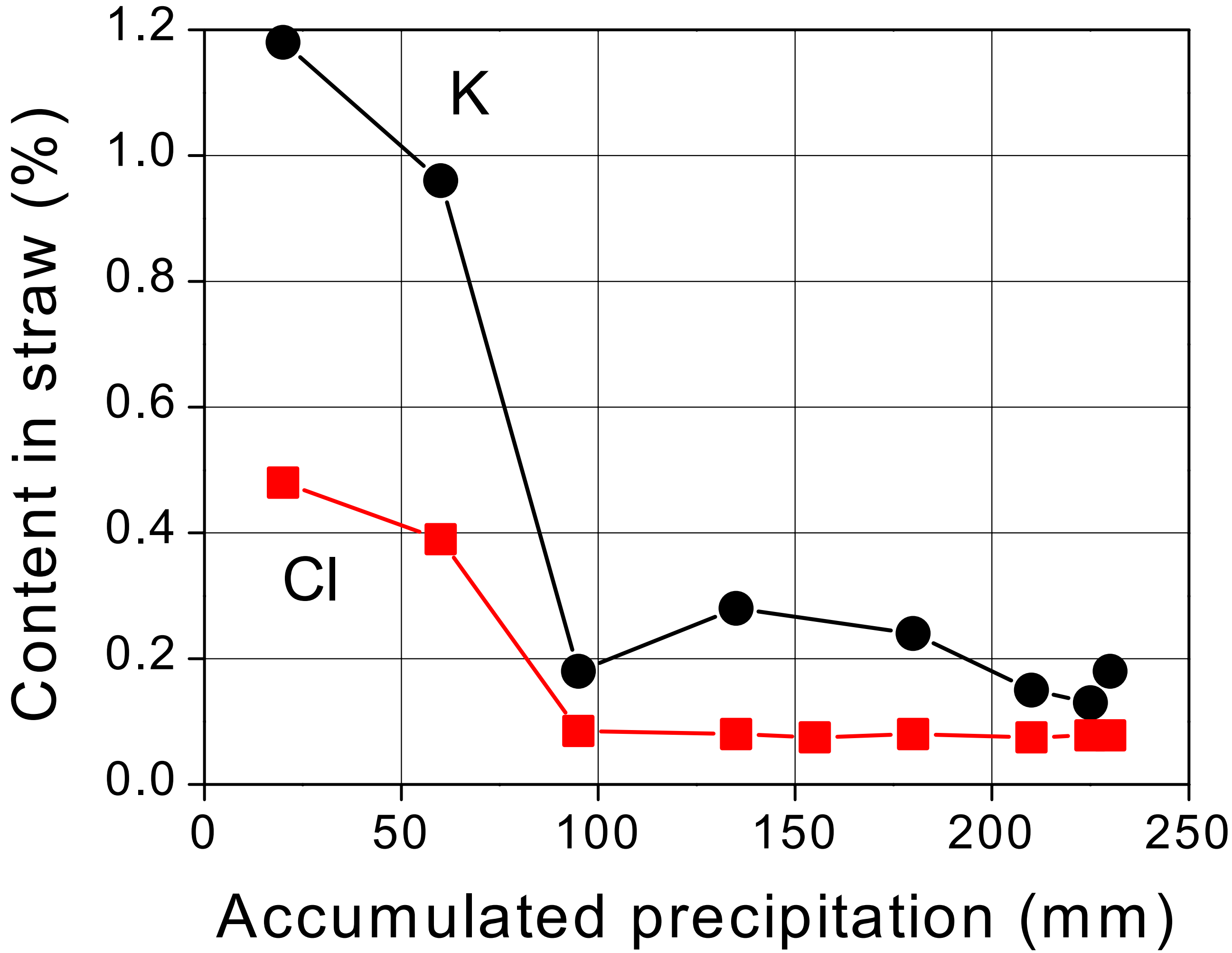
Biofuel characteristics



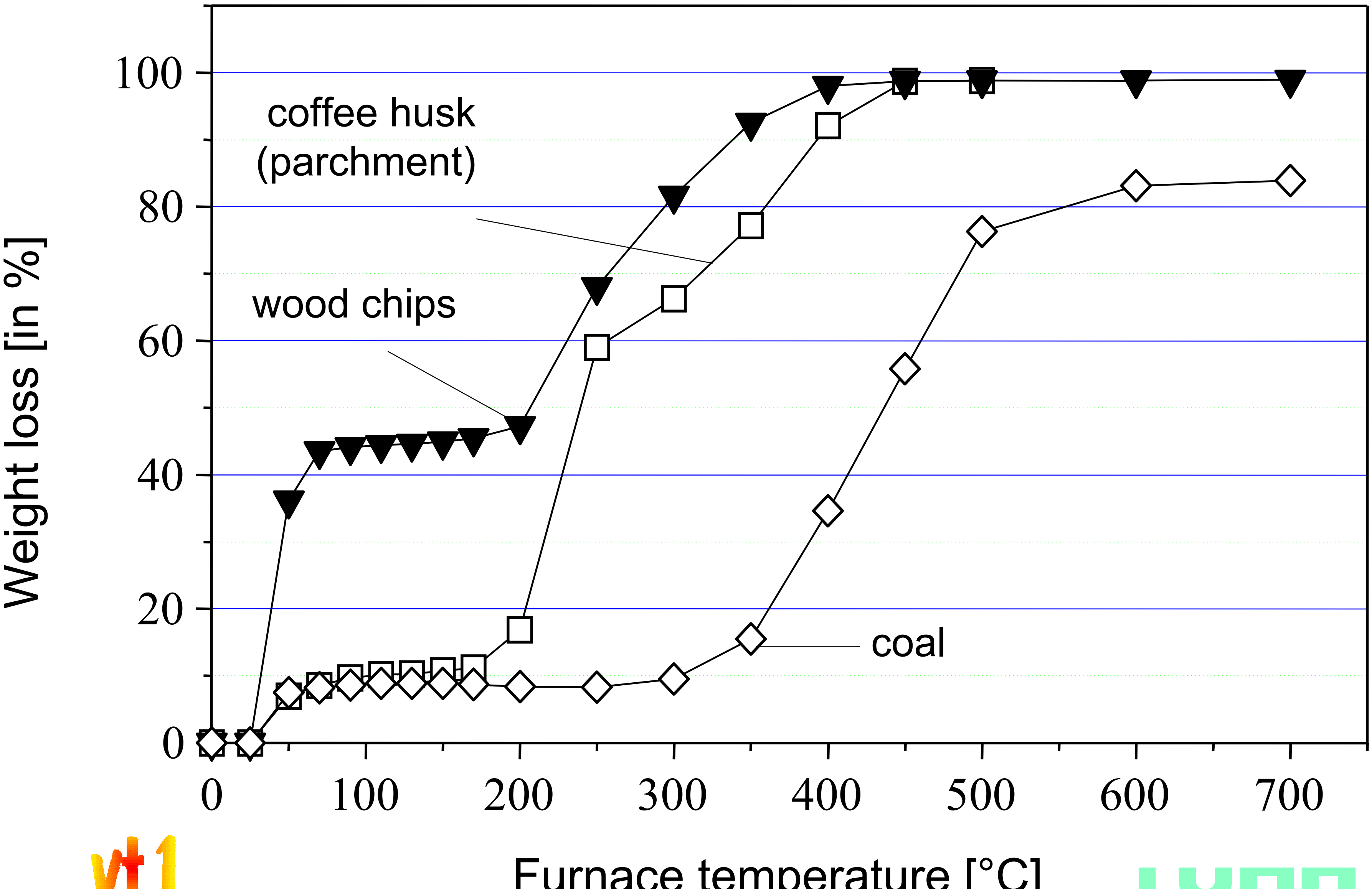
Content of K and Cl in wheat straw



Leaching of barley straw on the field



Weight loss analysis



Devolatilization characteristics

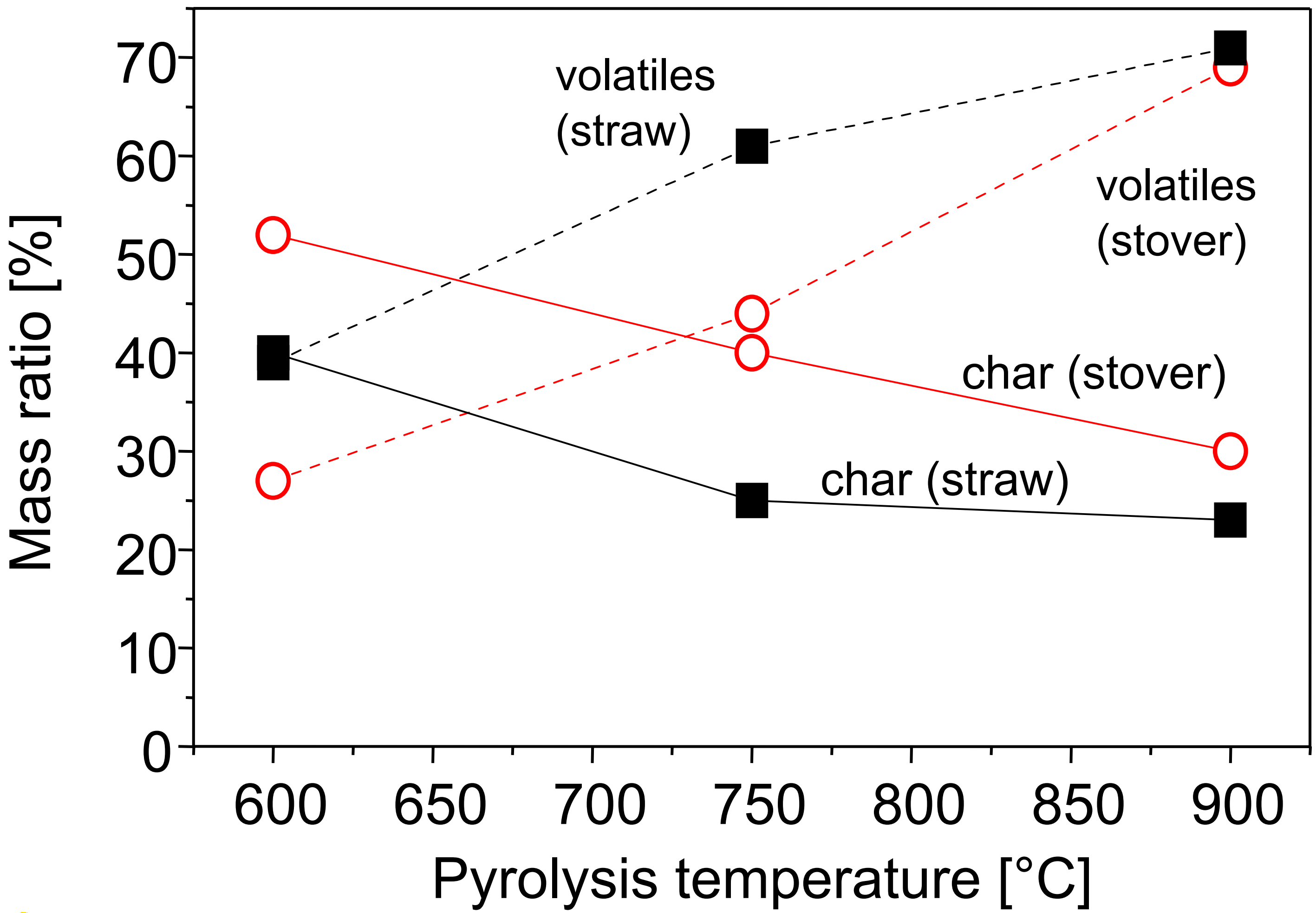
1. Experiments with increasing oven temperature

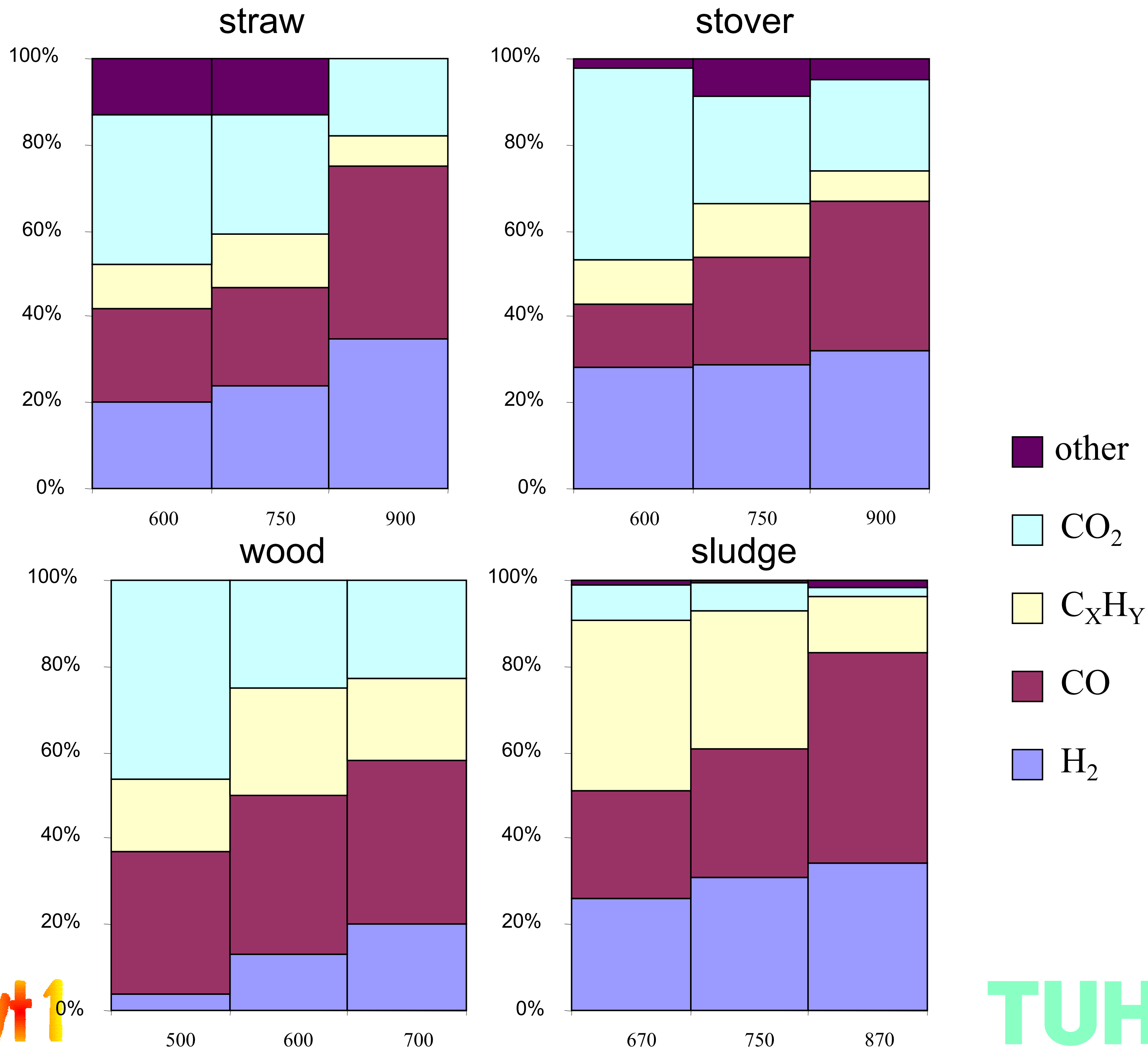
- devolatilization of biomass starts at low temperatures (160-200°C) and is completed around 500°C
- combustion of the char formed can take place at relatively low temperatures

2. Composition of the devolatilization products

- with increasing pyrolysis temperature the mass fraction of char decreases while the quantity of volatiles increases
- with increasing pyrolysis temperature the fraction of CO_2 in the volatiles decreases whereas (H_2 + CO) increase

Influence of the temperature on the relative quantities of char and gas




straw
stover
wood
sludge
100%
80%
60%
40%
20%
0%
600
750
900
500
600
700
670
750
870
other
CO_2
C_XH_Y
CO
H_2

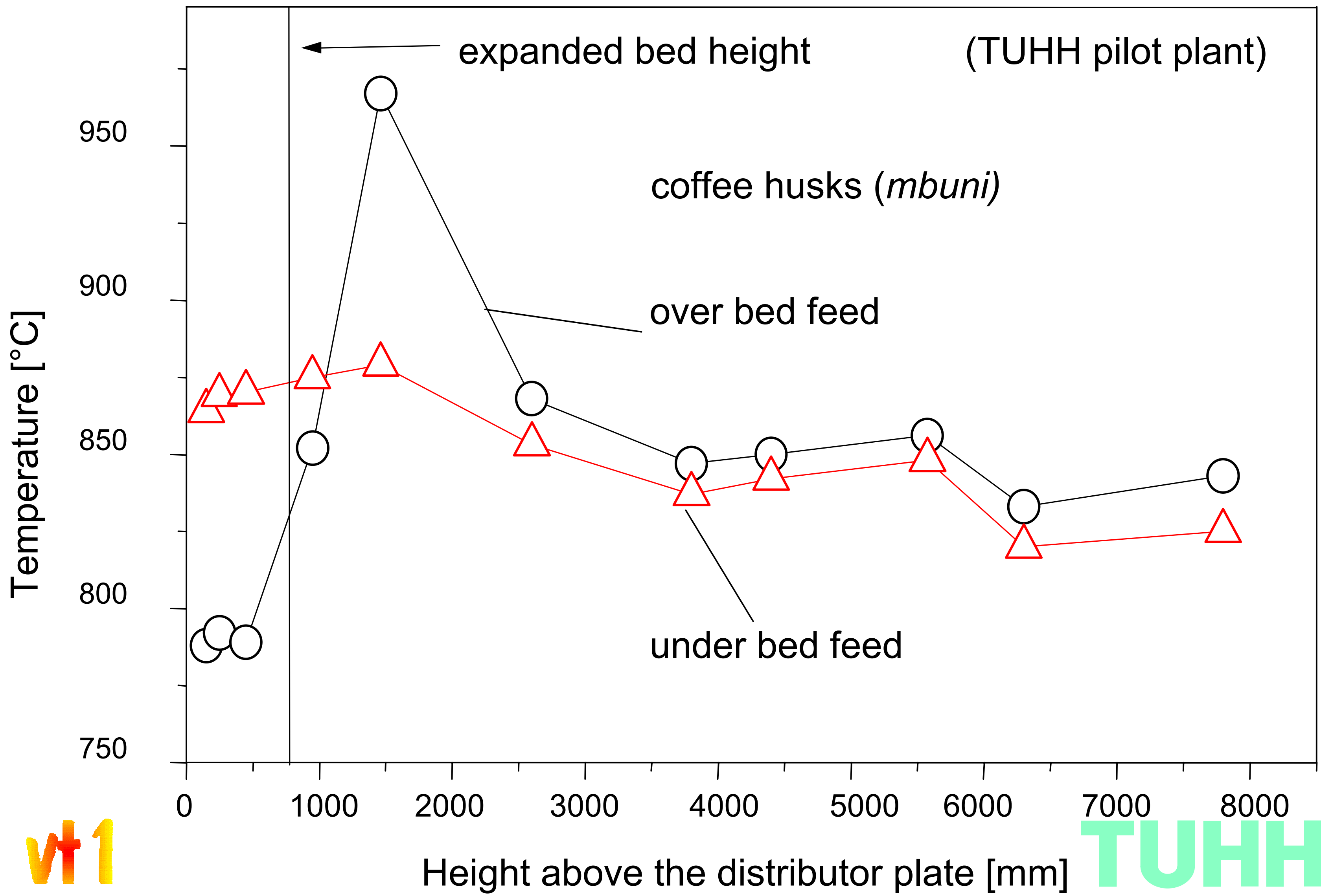
Effects of high volatile matter content

- in bubbling fluidized beds for sewage sludge combustion the freeboard temperature is generally higher than the bed temperature
- experiments with coffee husks show the same phenomenon for overbed feeding
- dry waste materials will release their volatiles close to the feed point since the lateral solids mixing is comparatively low; wet waste material will require more time for drying and devolatilization which provides an opportunity to mix over the bed´s cross-section

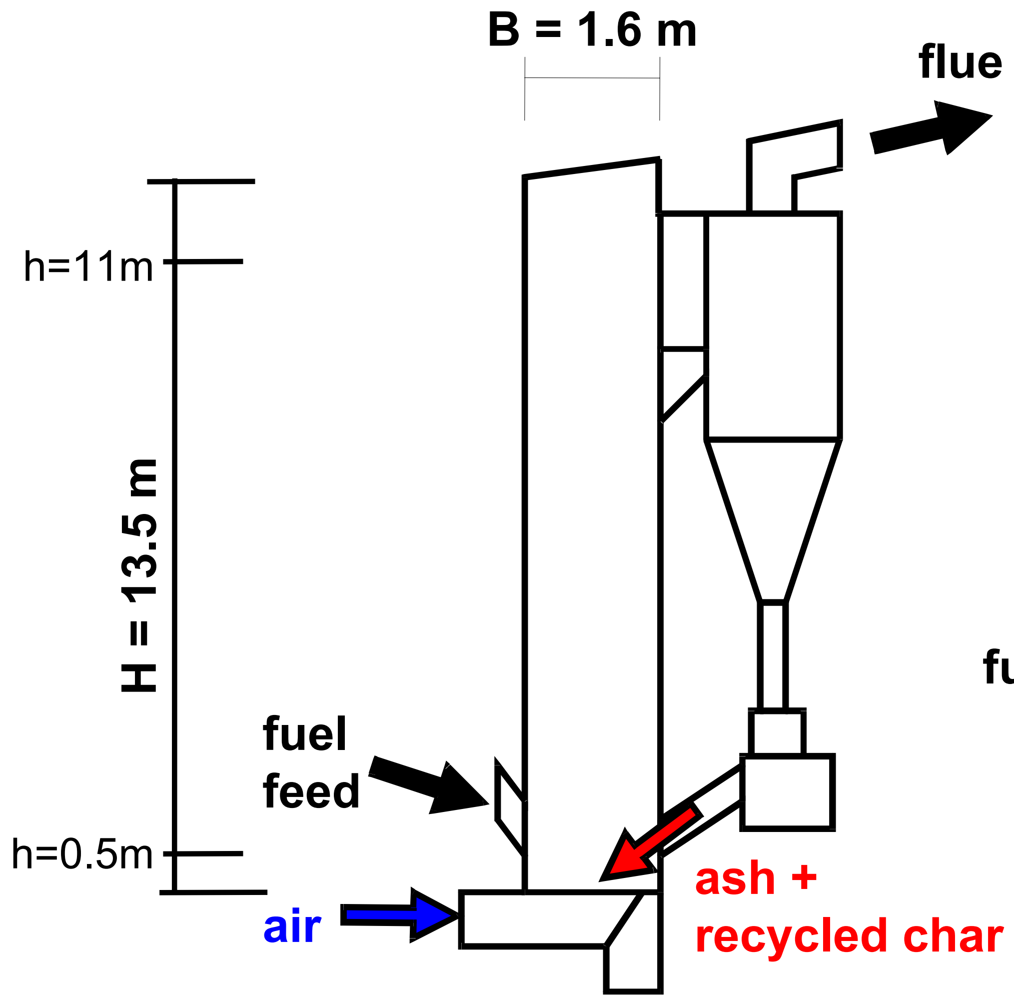
  ⇒ the high volatile matter content must be considered in the design of the fuel feeding configuration and the distribution of the combustion air

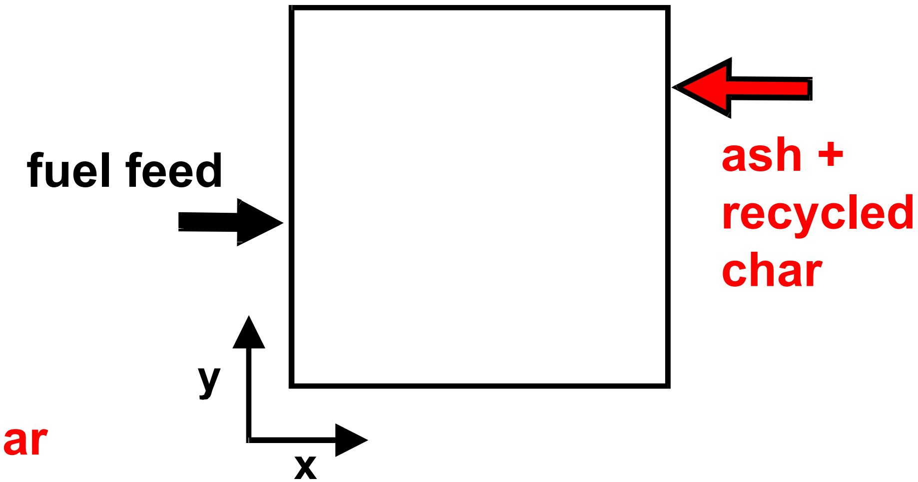
TUHH plants

Axial temperature profiles in a bubbling fluidized bed combustor



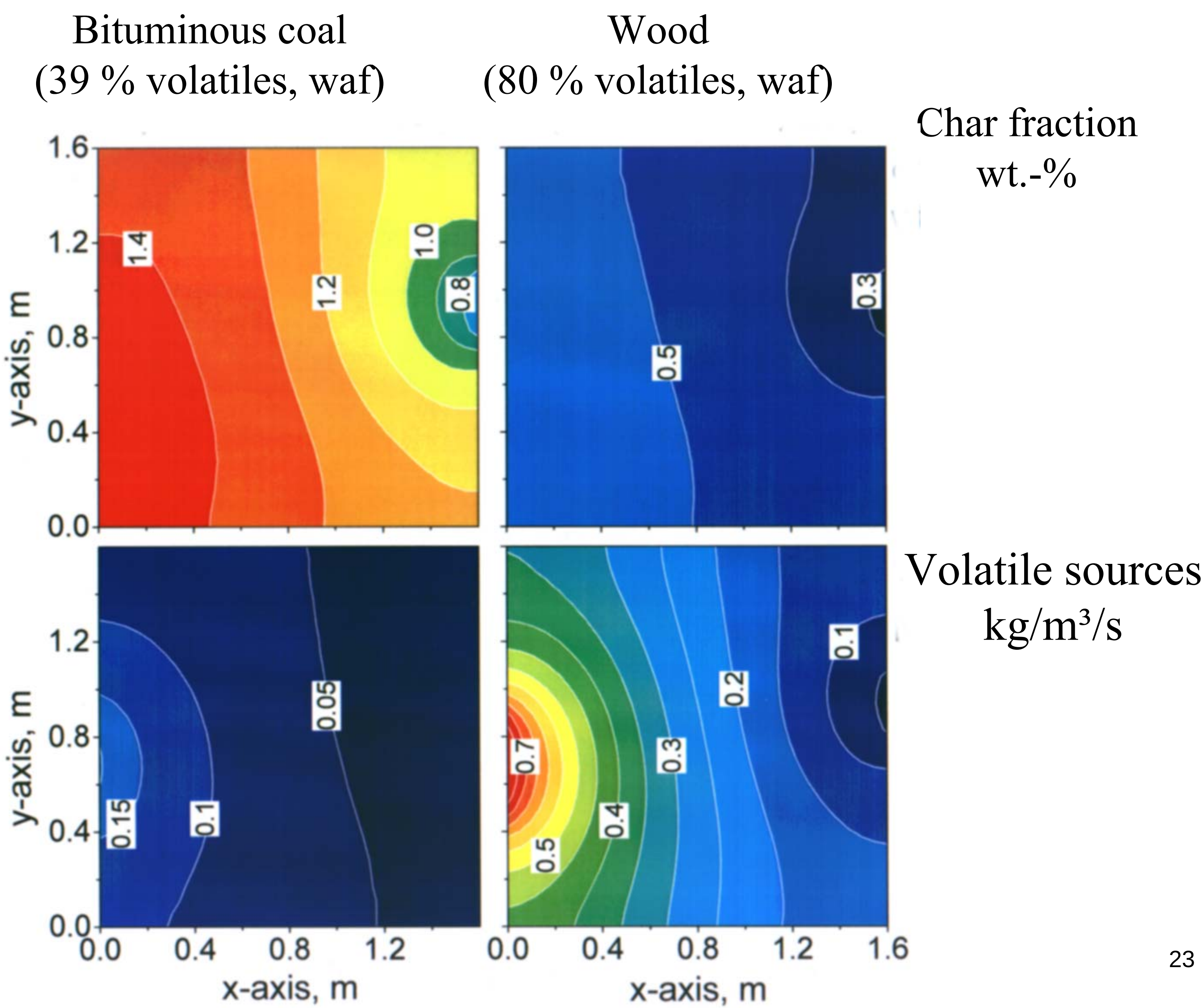
CFB-Boiler at Chalmers University, Sweden



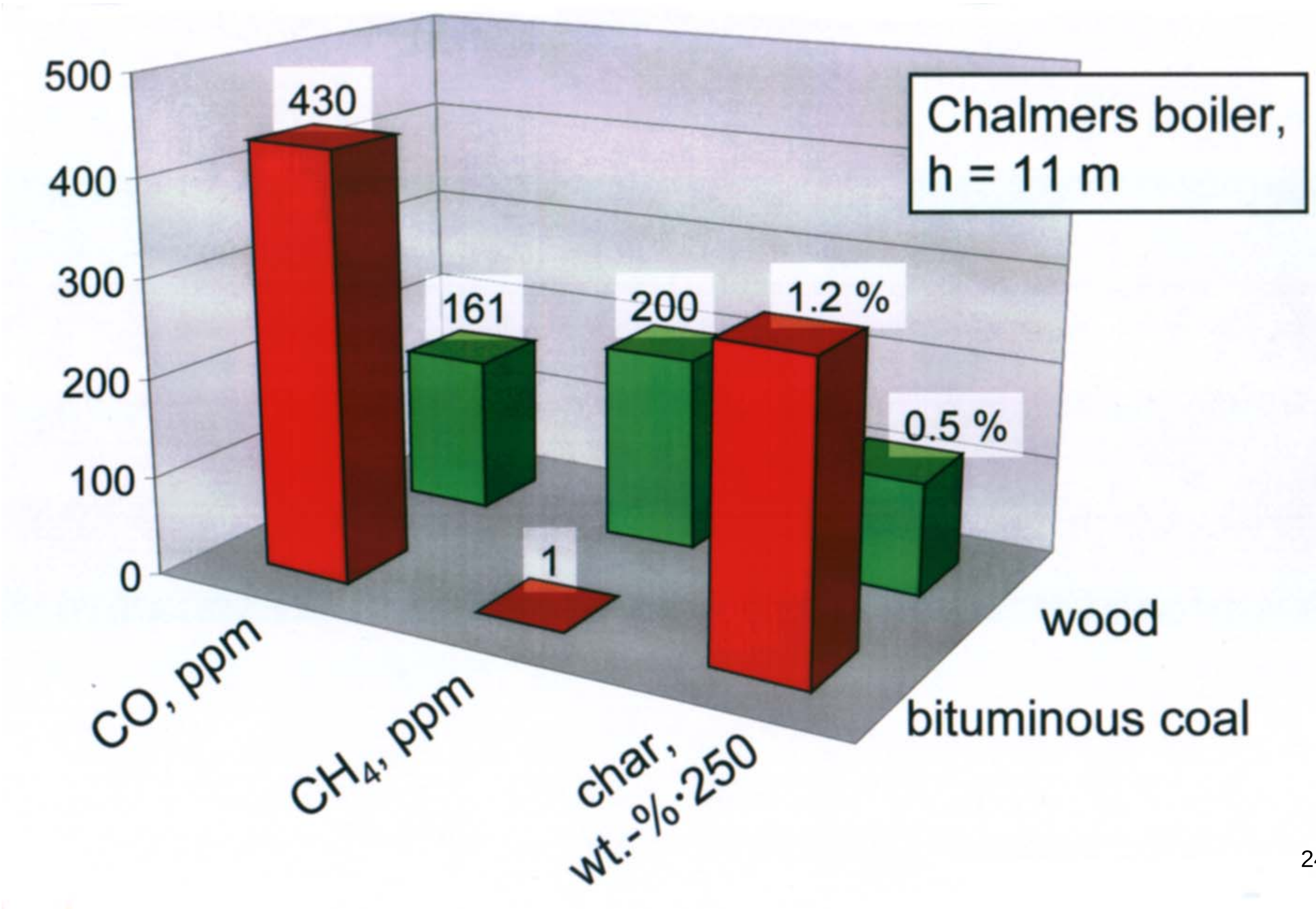


Chalmers boiler, single stage combustion, λ=1.2

Conditions at fuel feed level h=0.5 m



Cross-section averages of concentrations at the combustion chamber outlet (before cyclone)



Problems associated with the ash from agricultural residues

- bed material agglomeration in fluidized bed combustion
- fouling
- corrosion
- in case of co-combustion with coal the composition of the resulting ash is different from that of the coal ash

  → ash can perhaps no longer be used for cement making
- deactivation of the $DeNO_x$-catalyst in pf boilers

Chemical composition of ashes (wt.-%, wf)

	SiO_2	Fe_2O_3	P_2O_5	Al_2O_3	CaO	Na_2O	K_2O
cotton husk	10.8	1.9	4.0	1.3	20.7	1.3	49.6
soy husk	1.7	2.5	4.9	7.4	21.4	5.3	30.5
coffee husk (mbuni)	13.5	2.2	3.7	3.9	10.7	0.4	38.1
coffee husk (parchment)	16.6	2.4	3.4	4.5	9.8	0.5	36.9
sewage sludge	38.3	12.5	15.4	14.8	9.1	2.2	2.2
wood	12.8	5.2	2.1	4.1	45.2	0.6	0.5
peat	24.6	8.2	5.4	8.1	31.7	0.4	0.6
bituminous coal	43.7	10.2	0.3	24.7	5.8	0.9	3.2

→ ashes of agricultural residues are characterized by high contents of K_2O and (in some cases) Na_2O

Ash melting temperatures

	K_2O, wt.-%	initial deformation temperature, °C	hemisphere temperature, °C	flow temperature, °C
straws				
barley	40.3	730 – 800	850 – 1050	1050 – 1200
oat	40.3	750 – 850	1000 – 1100	1150 – 1250
rye	19.2	800 – 850	1050 – 1150	1300 – 1400
Wheat	6.6	900 – 1050	1300 – 1400	1400 – 1500
grains				
rye*		710		810
wheat*		687	887	933
wood				
spruce*		1426	1600	1583
coals				
Colombian	2.2	1283	1353	1427
Russian	2.4	1282	1363	1404

* from Kaltschmitt & Hartmann

Agglomeration problems in fluidized bed combustion systems

- melting ash may act as a binder for bed particles

- alkali compounds may react with Si compounds of bed particles:

$2\ SiO_2 + Na_2CO_3 \rightarrow Na_2O{\cdot}2SiO_2 + CO_2$, melting point 874°C

$4\ SiO_2 + K_2CO_3 \rightarrow K_2O{\cdot}4SiO_2 + CO_2$, melting point 764°C

- if sufficient Fe_2O_3 is available the risk of agglomeration is reduced since reaction with the alkali compounds according to

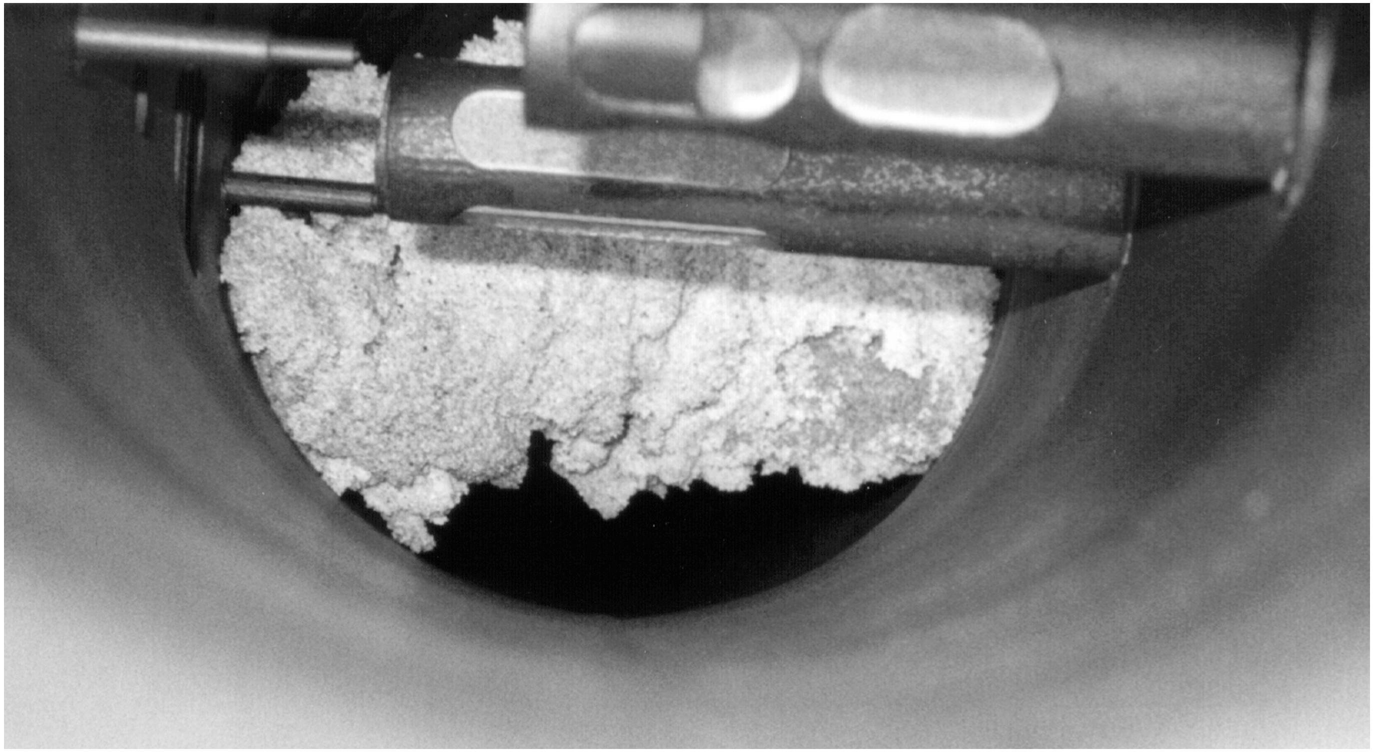
$Fe_2O_3 + X_2O \rightarrow X_2Fe_2O_4$

$Fe_2O_3 + X_2CO_3 \rightarrow X_2Fe_2O_4 + CO_2$

leads to compounds with melting temperatures > 1135°C

- beginning of agglomeration may be detected by fluctuations in bed temperature and pressure differential

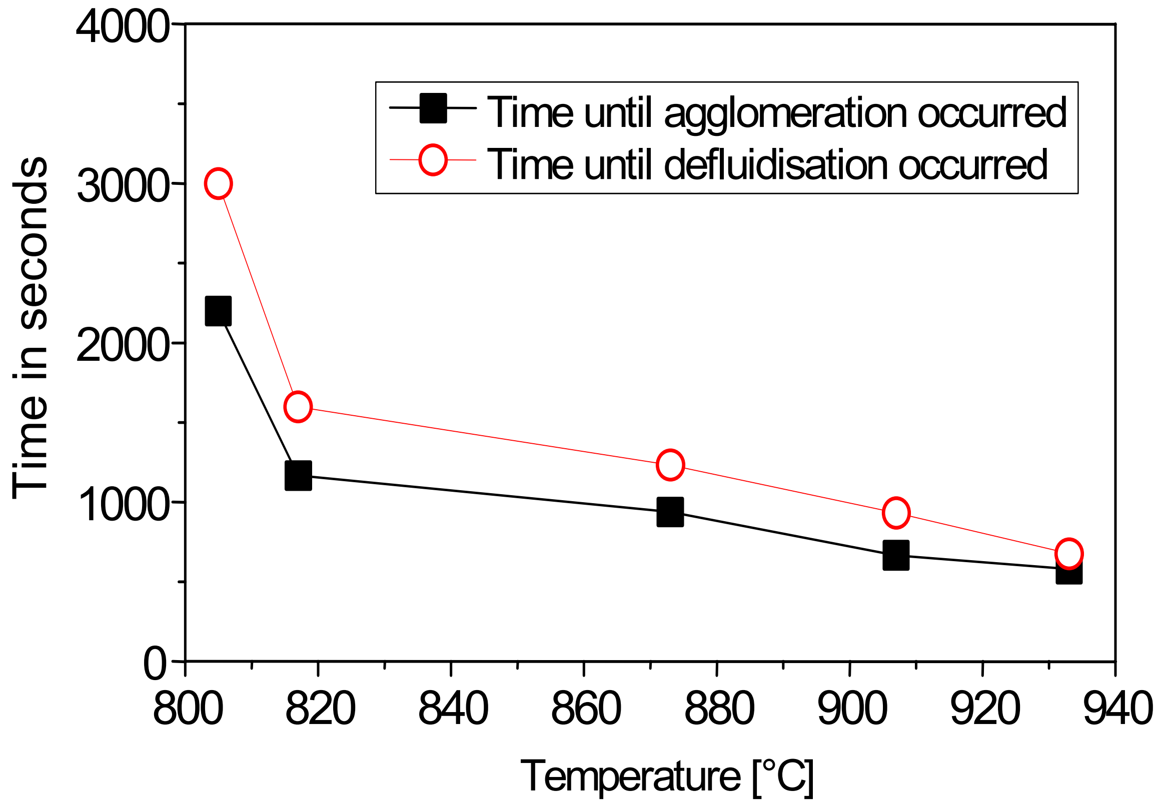
Combustion of coffee husks in the fluidized bed



overbed-feeding, view from the distributor level after bed has been taken out, agglomerate layer has formed in the freeboard

Agglomeration in fluidized bed combustors

- tendency towards agglo-meration may be counter-acted - to a limited extent - by
  - vigorous movement of the bed particles at high fluidizing velocity (circulating rather than bubbling fluidized bed)
  - use of coarser bed material



- increasing bed temperature increases the risk of agglomeration

How to reduce the risk of agglomeration?

- ash melting may be estimated from analysis:
- flow temperature T_{FP} = 1369 – 43.4 K + 192.7 Ca – 698 Mg, °C, were K, Ca, Mg are the contents of the elements in wt.-%

  → Ca-containing additives may be used to increase T_{FP} of fuel ash (limestone injection into the splash zone of a rice stalk fluid bed combustor prevented fouling)

  → other additives have also turned out to be effective (addition of 3 wt.-% kaolin to chopped oat straw increased deformation temperature from 770 to 1200-1280 °C

- Change of bed material sand against other materials (dolomite, alumina, ...)

→ Saxena et al. cofired peanut hull pellets with propane: agglomeration with silica sand, no agglomeration with alumina

How to reduce the risk of agglomeration?

→ blending of risky fuels with other fuels (e.g. blending of coffee husks with 20 % coal containing 40 % ash reduced K in fuel ash from 43.8 to 13.5 %)

→ leaching of K from straw by rain increases initial deformation temperature by 100-150 K

Slagging and fouling

- is quite often experienced in combustors firing 100 % straw
  →Muthukrishnan et al. (1995) in 10 MW FBC plant firing rice stalk experienced ash deposition on superheater tubes in flue gas path
  →for straw combustion in grate-fired boilers in Denmark a lot of trouble (ash fusion on the grate, slagging in the furnace, fouling on convective surfaces) is reported
- in coal industry an alkali index is used
  - above 0.17 kg alkali/GJ: fouling probable –

  e.g. 0.07 kg/GJ for a polish coal, but 1.0 kg/GJ for rice hulls, 1.1 kg/GJ for wheat straw, 1.6 kg/GJ for rice straw

  →fouling must be expected with agricultural residues and has to be taken into account in the design and operation of the combustion system

Corrosion

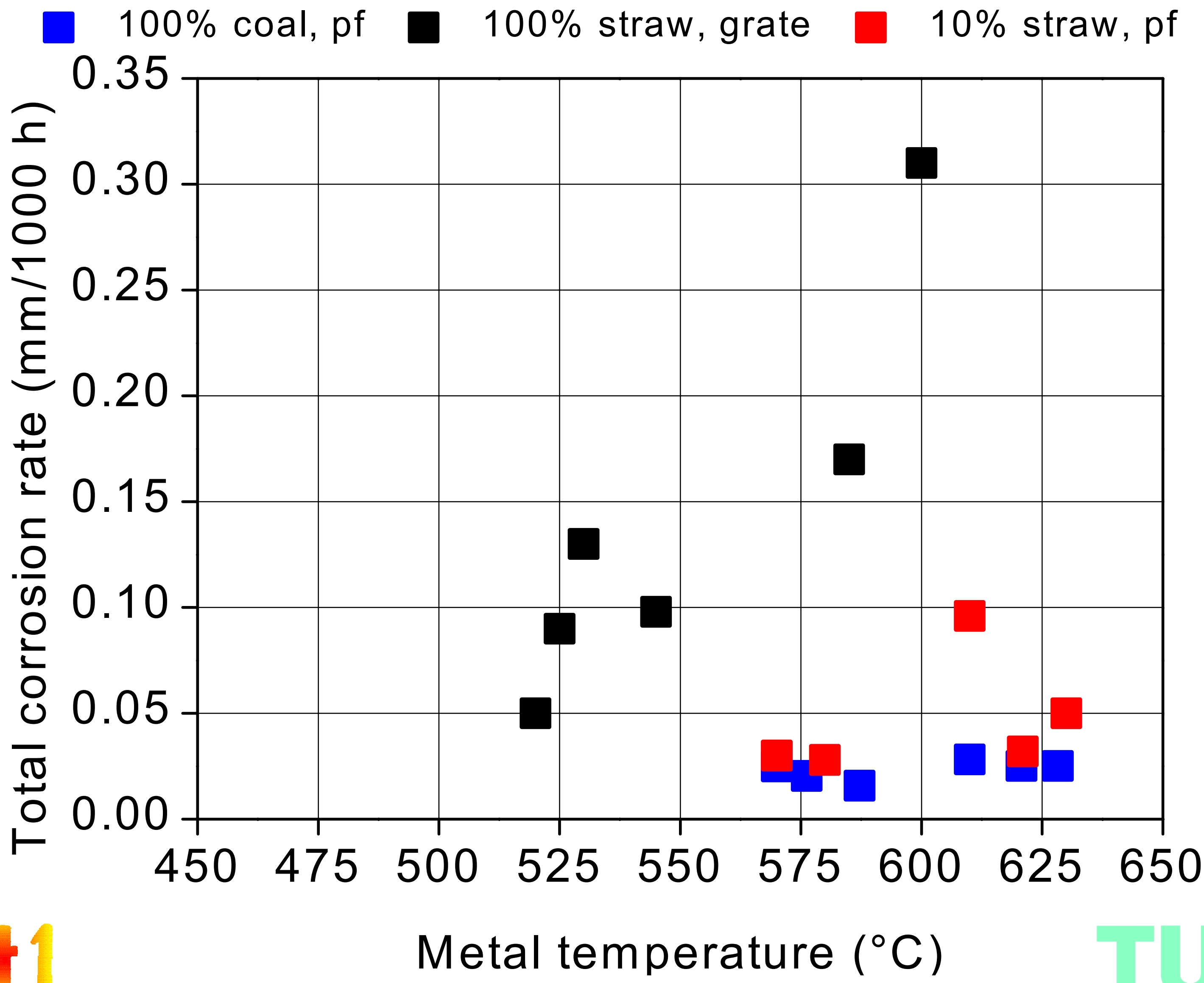
- is a problem in the mono-combustion of straw: in Danish straw-fired district heating boilers underneath ash deposits red layers of corrosion products found on convection tubes

- corrosion rates may be acceptable for co-combustion with coal if the energy share of the straw is about 10-20 %

- potassium and chlorine are the key elements

Corrosion tests at superheater probes

Material: X20CrMo V12.1 (Spliethoff 1999, Sander 2000)



Emissions from the combustion of agricultural residues

- NO_x: single-stage combustion of

rice husk	200-370	mg/m^3
straw	400	mg/m^3
coffee husk	400	mg/m^3

  →staged combustion may be necessary
- SO_2: due to low content in fuel no special measures required
- HCl: typically 20-120 mg/m^3, whether HCl washing is necessary depends on legal conditions (EU directive for waste combustion applies for co-combustion but not for mono-combustion, special regulations for biomass fired boilers)
- dioxins: generally less than 0.1 ng TE/m3 (Danish straw fired power plants < 0.01 ng)
- particulate emissions: 80 % of the ash particle mass released from the combustion of wood and grass is associated with particle sizes < 1 μm

Legal issues associated with co-firing of wastes

Legal basis for EU:

Directive 2000/76/EC of December 4, 2000
on incineration of waste

- Directives 86/369/EEC, 89/429/EEC, 94/67/EC are replaced as from December, 2005
  →one directive now for waste and hazardous waste incineration and co-incineration

- air emission limit values for co-incineration
  →emission limit values depending on the plant size and plant process

- emission limit values for discharge of waste water from cleaning of exhaust gases

Operating Conditions

- For slag and ashes: Total Organic Carbon (TOC) content < 3 % or loss of ignition (LOI) < 5 % of the dry weight of the material
- Waste incineration: temperature of the gas resulting from the process ≥ 850 °C for two seconds after the last injection of combustion air
- Co-incineration: temperature of the gas resulting from the process ≥ 850 °C for two seconds
- For hazardous wastes with a content of halogenated organic substances > 1 % the temperature has to be raised to > 1100 °C
- Automatic system required to prevent waste feed
  - during start up
  - when T ≤ 850 °C or ≤ 1100 °C
  - when exceeding any emission limit values

Emission limit values

Polluting substances	**EU-Directive** waste incineration Daily average values in mg/m^3 standard conditions, dry basis, 11 vol.-% O_2	**17^{th} BImSchV** waste incineration Daily average values in mg/m^3 standard conditions, dry basis, 11 vol.-% O_2	**13^{th} BImSchV** power plants Daily average values in mg/m^3 standard conditions, dry basis, 7 vol.-% O_2
TOC	10	10	20
CO	50	50	250
NO_X (as NO_2)	>6t/h: 200 <6t/h: 400	200	800
SO_2	50	50	400
HCl	10	10	50
HF	1	1	2
Hg	0,05	0,03 (since 1999)	-
Dioxins and furans	$0{,}1 \cdot 10^{-3}$	$0{,}1 \cdot 10^{-3}$	-

German legislation for sludge combustion

- If heat release by sludge > 25 %
  → 17th regulation of the German federal immission law (17thBImSchV)

- If heat release by sludge < 25 %
  → averaged emission limits of the 13thBImSchV regulation (for power plants) and17th regulation
  → mixing rule

- If heat release by sludge < 25 %
  → emission limits have to be kept as if the heat release of the waste were exactly 10 %

Determination of the heat release

$$\frac{\dot{m}_{waste} \cdot H_{u,waste} + \dot{m}_{support} \cdot H_{u,support}}{\left(\dot{m}_{waste} \cdot H_{u,waste} + \dot{m}_{support} \cdot H_{u,support}\right) + \dot{m}_{fuel} \cdot H_{u,fuel}}$$

m_{waste}: mass flux of waste

m_{fuel}: mass flux of normally authorised fuel

$m_{support}$: mass flux of support fuel

$H_{u,waste}$: heating value of waste

$H_{u,fuel}$: heating value of normally authorised fuel

$H_{u,support}$: heating value of support fuel

Mixing rule

$$C_{mix} = \frac{V_{fuel} \cdot C_{13} + V_{waste} \cdot C_{17}}{V_{fuel} + V_{waste}}$$

C_{mix}	total emission limit value
C_{13}	emission limit value 13thBImSchV
C_{17}	emission limit value 17thBImSchV
V_{fuel}	exhaust gas volume from the incineration of waste at standard oxygen concentration of 7 %
V_{waste}	exhaust gas volume from the incineration of the fuel normally used in the plant at standard oxygen concentration of 11 %

Reference conditions

Total emission limit values are referred to reference oxygen concentrations:

$$O_{2,ref} = \frac{V_{fuel} \cdot O_{2,13thBImSchV} + V_{waste} \cdot O_{2,17thBImSchV}}{V_{fuel} + V_{waste}}$$

It is forbidden to convert an emission value which is measured at a lower O_2 value in off gas than the reference O_2 value. If the O_2 concentration in the exhaust gas is higher than the reference concentration it must be corrected.

EU-Directive

– for co-combustion of waste:
  $\Rightarrow$ emission limit values for co-incineration plants (Annex II) according to mixing rule

– for co-combustion of hazardous waste:

- heat release of hazardous waste < 10 %:
  emission limits have to be kept as if the heat release of the waste was exactly 10 %

- heat release of hazardous waste $\geq$ 10 %:
  emission limit values for co-incineration plants (Annex II) according to mixing rule

- heat release of hazardous waste > 40 %:
  emission limit values for incineration plants (Annex V)

Mixing rule for EU-Directive - (Annex II)

Emission limit value C depends on volume fraction of the exhaust gas from waste incineration, the plant size and the plant process.

$$C = \frac{V_{waste} \cdot C_{waste} + V_{proc} \cdot C_{proc}}{V_{waste} + V_{proc}}$$

C : total emission limit value and oxygen content for standardisation respecting the partial volumes

V_{waste} : exhaust gas volume resulting from the incineration of the waste

C_{waste} : emission limit values set for incineration plants (Annex V)

V_{proc} : exhaust gas volume resulting from the combustion of fuels normally used in the plant

C_{proc} : emission limit values set for certain industrial sectors (Annex II)

Standard conditions (EU)

- 273 K, 101,3 kPa, 11 % oxygen, dry gas in exhaust gas of incineration plants
- 273 K, 101,3 kPa, 3 % oxygen, dry gas in exhaust gas of incineration of waste oil
- 273 K, 101,3 kPa, 10 % oxygen, dry gas in exhaust gas of cement kilns

co-incineration:

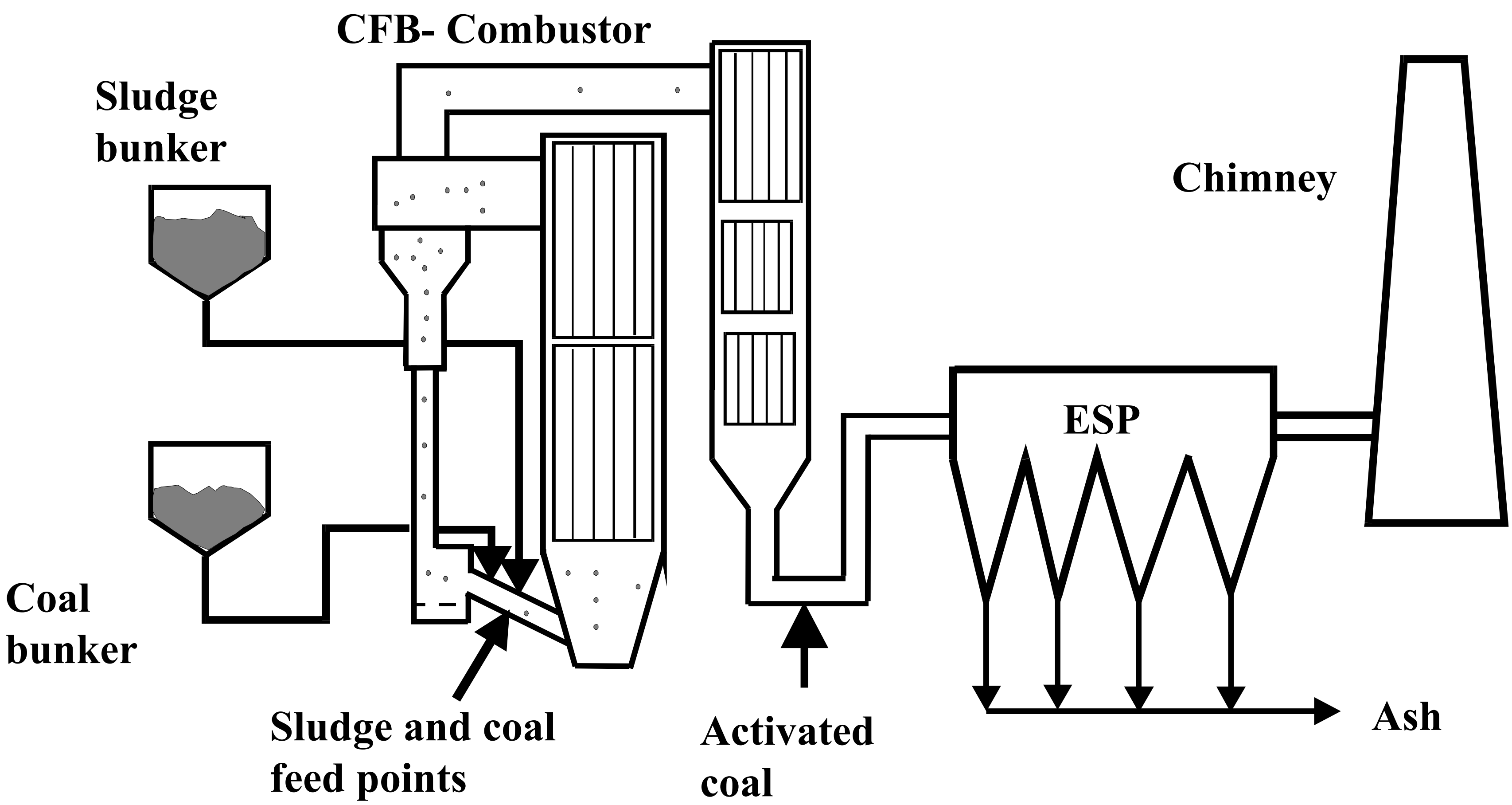
- in the case of co-incineration, the results of the measurement shall be standardised at a total oxygen content as calculated in Annex II
- oxygen content for calculation of C_{proc}:
  - solid fuels: 6 %, dry gas
  - biomass: 6 %, dry gas
  - liquid fuels: 3 %, dry gas

VGB

- Hochkant

Grenaa

Co-combustion of sewage sludge in Rheinbraun's Berrenrath Plant



Co-combustion experience from Rheinbraun's Berrenrath Plant

- 120,000 t/a mechanically dewatered sludge is incinerated (about 40,000 t d.m. /a)
- Permission granted to burn 65,000 t d.m./a
- no problems with emissions after injection of active coke before the ESP was installed
- Hg emission is now 4µg/m³

Tacoma steam power plant - USA

Details

Owner -Tacoma Public Utilities

Capacity - 50 MWe

Furnace - FBC

Fuel - coal: 20 %
wood: 60 %
RDF: 20 %

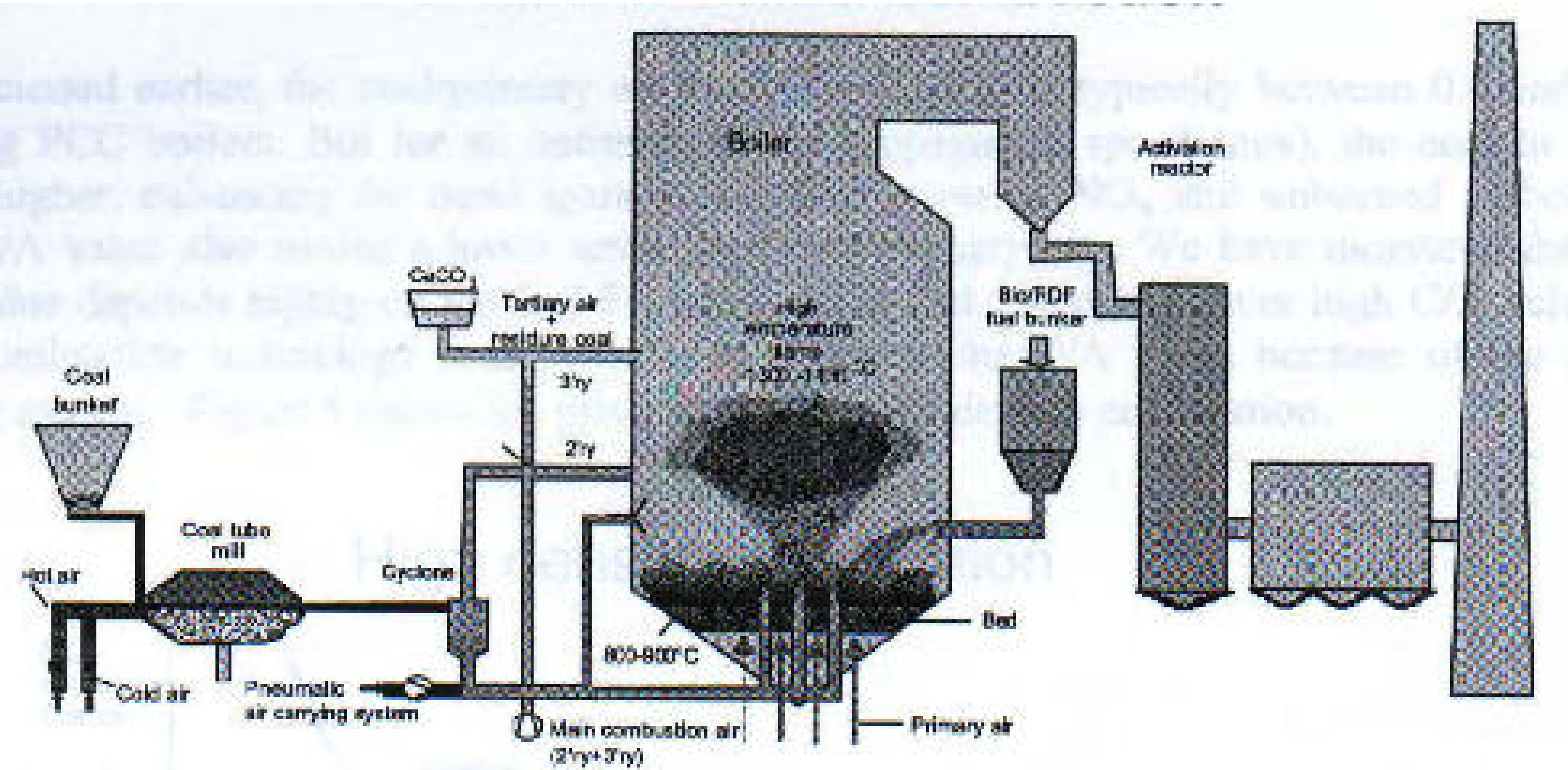
Special features

- periodical removal of agglomerated bed media, glass, metals etc from bed
- 93 % HCl removal

Experience gained at Tacoma steam power plant

- Co-combustion from 1991 to 1998
- All emission limits met
  - FBC+limestone injection led to low SO_2 and NO_x
  - 90 % HCl removal
- All byproducts recycled
  - Fly ash used for sludge stabilization and cement production
  - Aggregates used as road base material
- Economics
  - the renovation of the plant cost $45m million
  - Project received grant from state of $ 15 million
  - Plant was saving municipality of $ 1 million per year by burning RDF
  - From 1997 the plant was making losses of $ 2 million per year due to unfavorable costs of wood and cheap electricity from public utilities

HAT-BFB multifuel combustion



HAT-BFB multifuel combustion

- Biomass and part of coal burned in bed at low temperature (800-850 °C) to avoid agglomeration

- Remaining part of coal burned in freeboard at 1350-1450

- High freeboard temperature
  - Leads to higher combustion efficiency
  - Low NOx based on the reburning technique

- Large scale demonstration plant
  - at Rauhalahti Power Plant in Finland
  - Fuel: wood, bark and coal

Experts ranking of co-firing technologies

By 80 experts at EU Seminar in Cottbus, 2000

Fuel mixture	PF	FBC	CFB	PFBC	IGCC	GC
Coal and biomass	2,6	3,3	3,5	1,9	2,3	2,6
Coal and residual wood	2,3	3,4	3,8	1,7	2,0	2,6
Coal and straw	1,9	2,5	3,0	1,6	1,6	1,9
Coal and sewage sludge	2,7	2,9	3,2	2,4	2,5	2,4
Coal and petroleum coke	2,1	2,0	2,5	2,1	3,7	2,3
Coal and RDF	2,1	2,6	3,1	1,9	3,0	2,7
Coal and municipal waste	1,7	2,6	2,9	1,6	2,7	2,7
Coal and plastics	1,9	2,3	2,3	2,0	2,7	2,9
Average of ranking	2,2	2,7	3,0	1,9	2,6	2,5
Position of ranking	5	2	1	6	3	4

Conclusions

- Agricultural residues and sewage sludges are CO_2-neutral fuels. Their use contributes to the global reduction of CO_2 emissions.
- Agricultural residues are difficult fuels due to high alkali contents and handling properties.
- Co-combustion with coals in existing power stations is an interesting option.
- Sewage sludges provide income for power stations
- Agricultural residues will only be used to a greater extent if economic incentives are sufficient.
  $\rightarrow$ governmental programs, tax privileges and subsidies are necessary

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