# Primary measures for low-dust combustion – relevant findings

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# Introduction (I)

- In 2007 in Austria about 18% of the primary residential heating systems were based on biomass combustion.
- These systems provided about 88% of the $PM_{10}$ emissions of the residential heating sector.
- Mainly old combustion systems (logwood boilers and stoves), which amount to 85% of the installed residential biomass heating systems, are responsible for this high contribution to $PM_{10}$ emissions.
- In many other European countries a comparable situation prevails (e.g. in Germany or Sweden).

# Introduction (II)

- Current research work has shown that steady technological improvement of small-scale biomass combustion systems during the last decades has lead to a significant reduction of PM emissions.
  - old biomass logwood boilers and stoves:
    average PM emissions of 90 mg/MJ respectively 148 mg/MJ
  - modern biomass boilers and stoves
    average PM emissions of 20 to 50 mg/MJ
- However, even for modern systems further PM emission reduction potentials exist which should be exploited with the aim to approach towards zero dust emission technologies.

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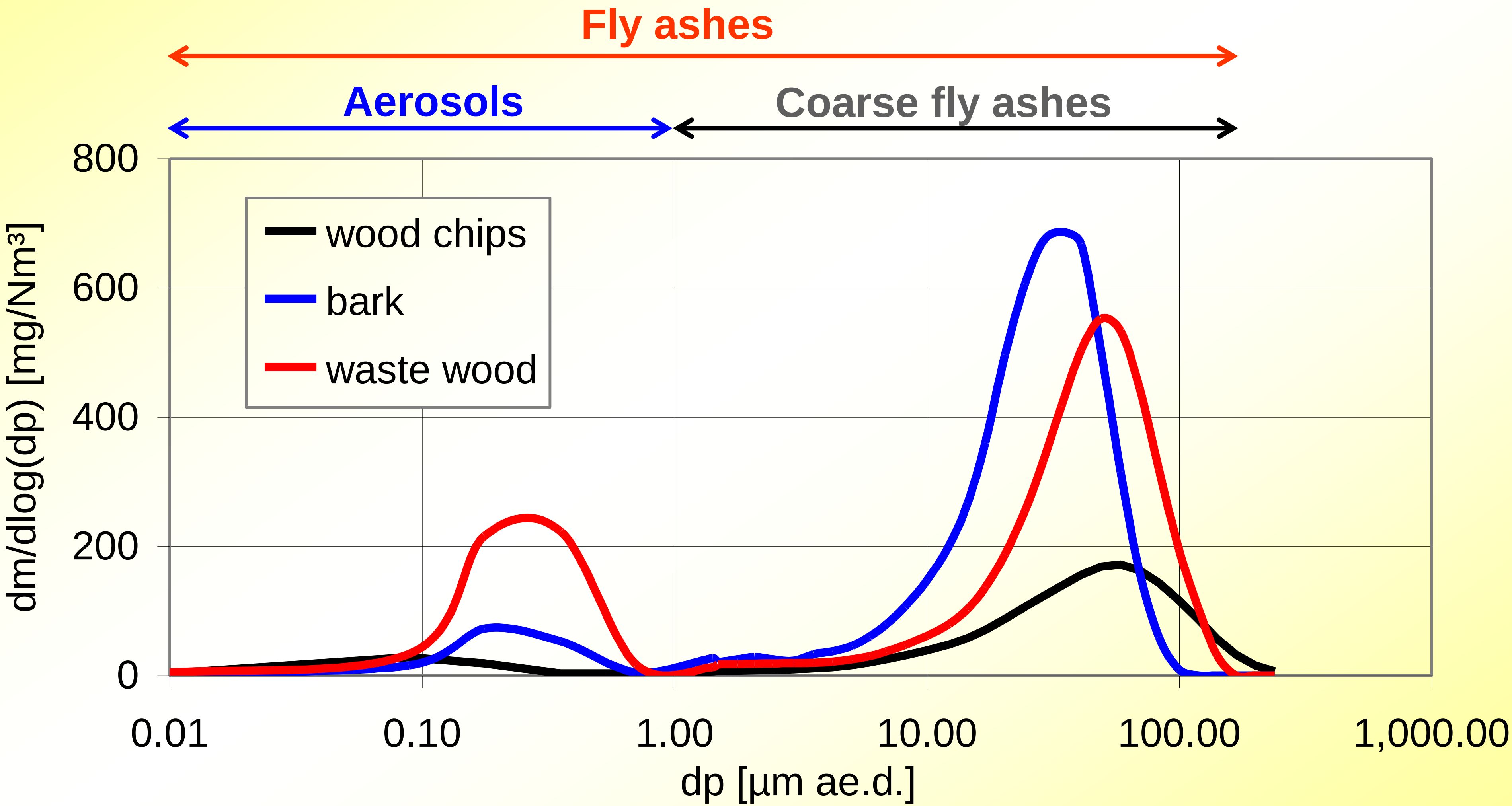
# Particulate emissions from fixed-bed biomass combustion systems – categorisation of PM emissions (I)




Data related to dry flue gas and 13 vol.% $O_2$; results from grate-fired combustion systems

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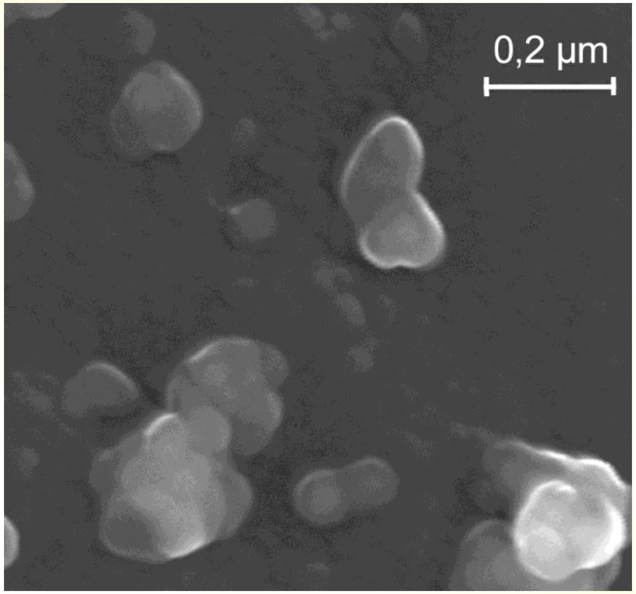
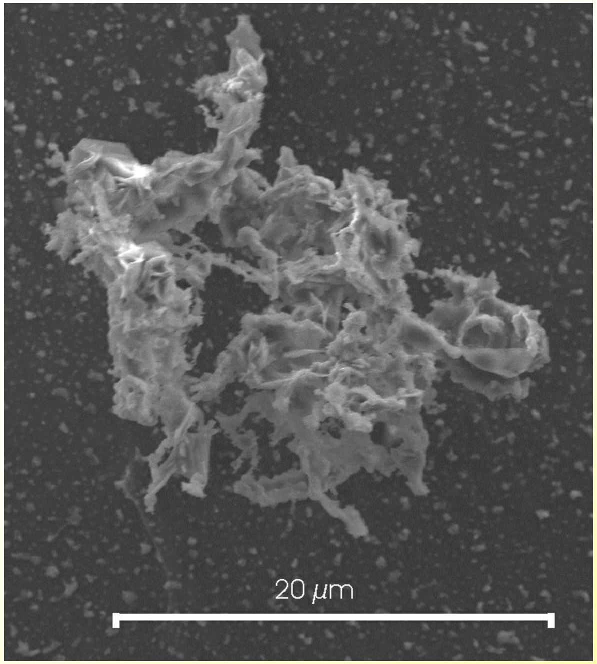
# Particulate emissions from fixed-bed biomass combustion systems – categorisation of PM emissions (II)

**Organic aerosols, soot**


**Inorganic aerosols ($K_2SO_4$, KCl, $K_2CO_3$, ZnO, ...)**




**Coarse fly ashes**




Explanations:

Left: agglomerate of organic aerosols and soot particles; sampling from the flue gas of a stove at insufficient burnout conditions; fuel: beech logwood

Middle and right: aerosols and coarse fly ashes sampled in a grate fired combustion unit at good burnout conditions; fuel: beech wood chips

Images from scanning electron microscopy (SEM)

# Formation of PM emissions during biomass combustion

## ➢ Coarse fly ash particles

- Entrainment of fuel, ash and charcoal particles from the fuel bed

## ➢ Inorganic aerosols

- Release of inorganic compounds from the fuel bed to the gas phase (most relevant elements: K, S, Cl, Na, Zn, Pb)
- Gas phase reactions (formation of e.g. $K_2SO_4$, KCl, $K_2CO_3$, ZnO etc.)
- Particle formation by nucleation and particle growth by condensation and coagulation

➔ strongly depend on the chemical composition of the fuel used

## ➢ Carbon containing aerosols (excluding carbonates)

- Originate from incomplete combustion
- Organic aerosols (condensed hydrocarbons)
- Soot

➔ can be avoided by achieving complete burnout

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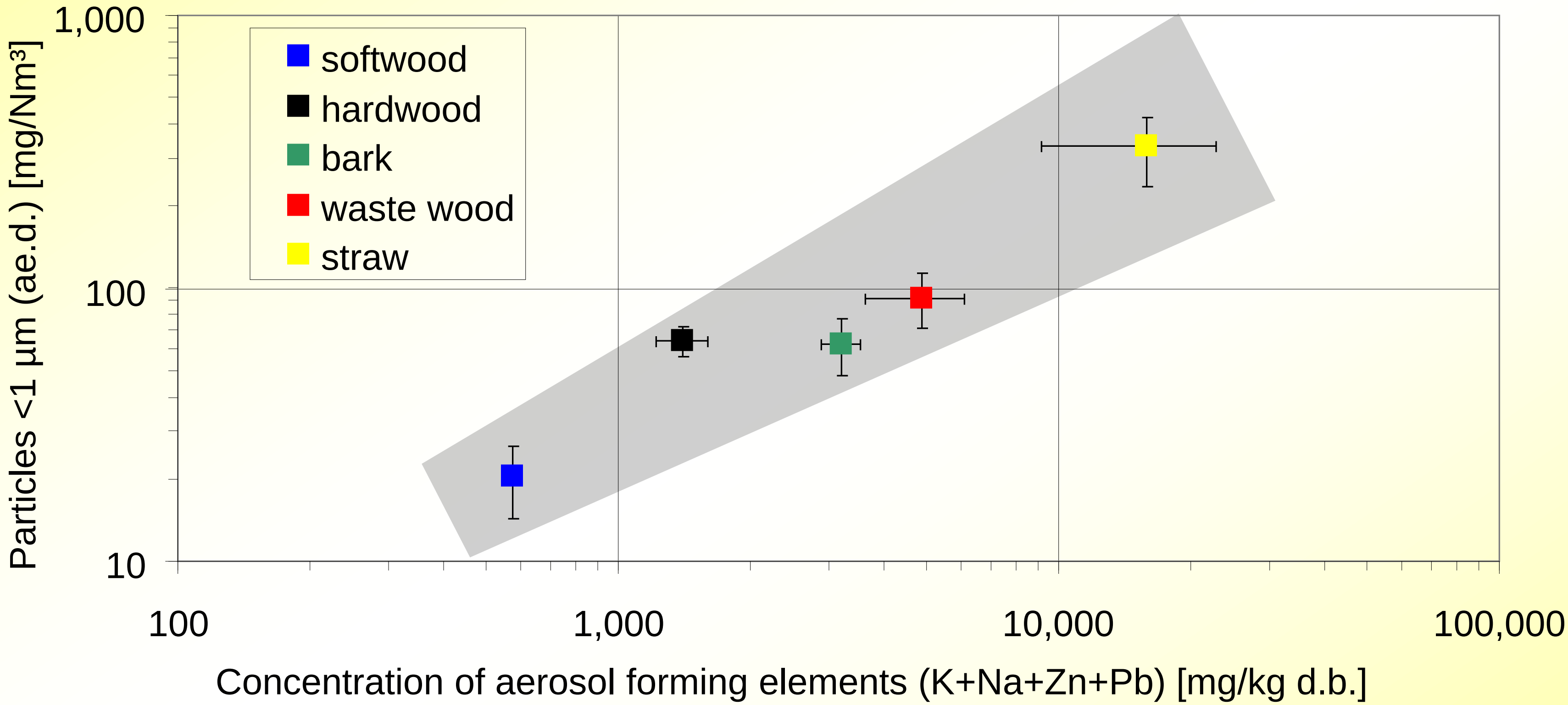
# Influence of the fuel used on the mass of inorganic aerosols formed




- Emissions at boiler outlet
- Summary of the data gained during the test runs at combustion plants with nominal fuel power between 0.4 MW and 110 MW; grey region: experiences from other projects
- Particle emissions related to dry flue gas and 13 vol% $O_2$

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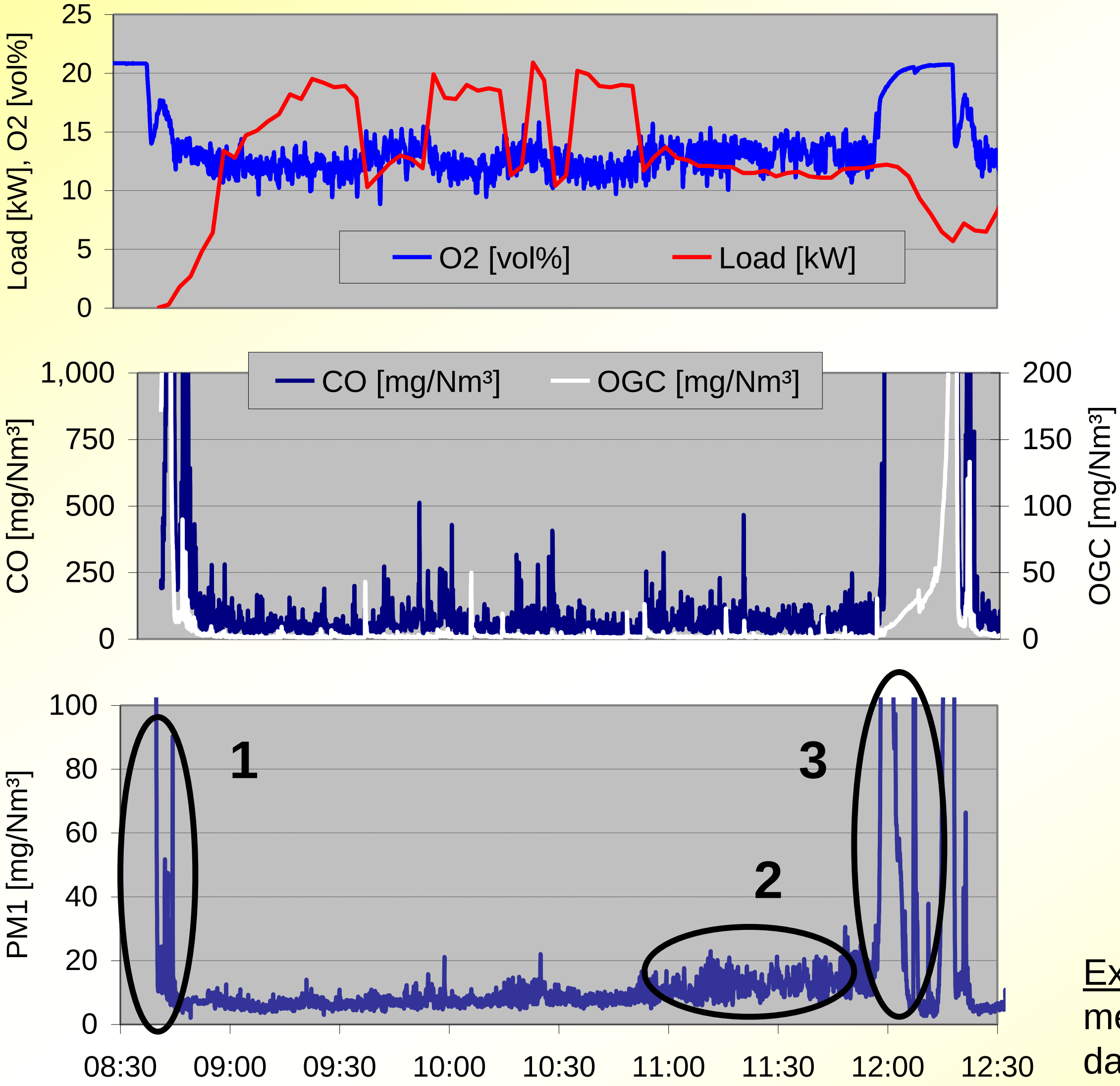
# Typical emission trend during pellet combustion in a modern automatic pellet boiler




- **Significant emission peaks (CO, OGC, PM) during**
  - **start-up (1)**
  - **shut down (3)**
- **Slightly increased emissions (CO, OGC, PM)**
  - **at partial load operation (2)**

Explanations:
measurements at a 20 kW state-of-the-art pellet boiler; data related to dry flue gas and 13 vol. % $O_2$

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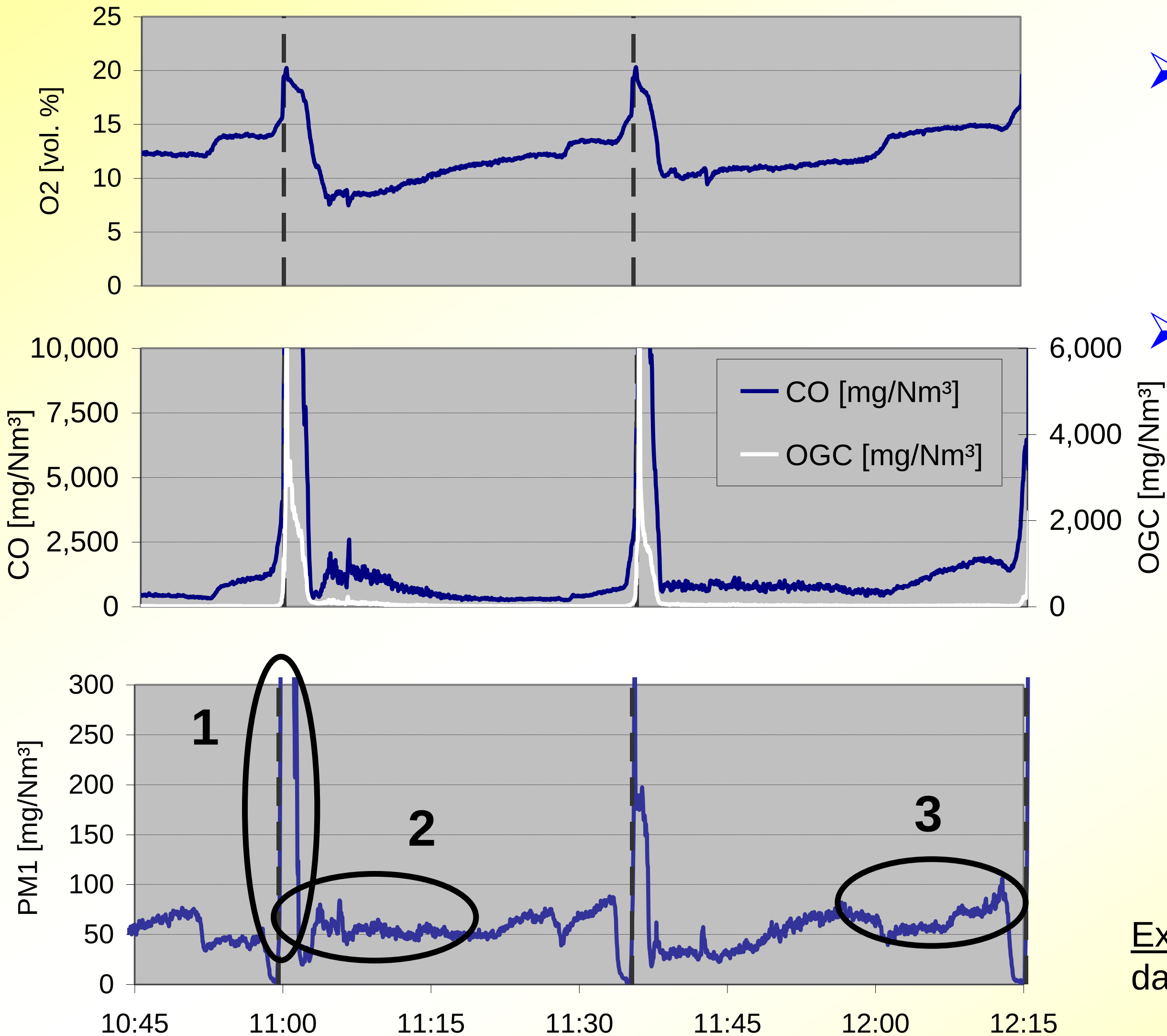
# Typical emission trend during batch combustion in a modern stove




- **Significant emission peaks (CO, OGC, PM) during**
  - **ignition phase (1)**
- **Increased emissions (CO, PM)**
  - **during phases with too low $O_2$ concentrations in the flue gas (2)** (in this case: <10 vol%)
  - **burnout phase (3)**

Explanations:
data related to dry flue gas and 13 vol. % $O_2$

# Primary measures for low-dust emission boiler and stove concepts – general aspects

- It must clearly be distinguished between automatically controlled boiler systems (pellet, wood chips, logwood) and batch combustion systems (stoves).

- General approach and objectives:
  - **All Systems:**
    reduction of coarse fly ash emissions to an almost zero emission level
  - **Batch combustion systems:**
    significant reduction of organic aerosol and soot emissions by burnout optimisation
  - **Automatically controlled boiler systems:**
    reduction of organic aerosol and soot emissions to an almost zero emission level by burnout optimisation at all operation conditions and additional reduction of inorganic aerosol emissions
  - **Generally, all measures which reduce CO and OGC emissions also contribute to a reduction of PM emissions**

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# Primary measures for low-dust emission boiler and stove concepts – reduction of coarse fly ash emissions

## ➢ Minimisation of entrainment of fuel, char and coarse fly ash particles from the fuel bed

- **appropriate grate and optimised geometry of the primary combustion zone**
  - keep the fuel bed as undisturbed as possible
  - keep the combustion air velocities in the bed as well as the flue gas velocities at bed exit low
- **appropriate separation zones with low flue gas velocities or sharp turns of the flue gas flow direction in order to precipitate coarse fly ashes**

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# Primary measures for low-dust emission stove concepts – reduction of organic aerosol and soot emissions (I)

## ➢ Ignition phase

- Should be kept as short as possible
  ➔ high flue gas temperatures and low $O_2$-concentrations in the flue gas (around 10 vol% d.b.) should be reached within short time
- Increase the burning rate at the beginning of a batch but avoid too high burning rates which can lead to a lack of oxygen at the beginning of the subsequent main combustion phase
- Intelligent geometry regarding the window purge air supply
- Application of air staging
  (introduction of tertiary air besides window purge air)
- Introduction of advanced automatic control concepts which include the injection of primary air through the fuel bed at the beginning of each batch

# Primary measures for low-dust emission stove concepts – reduction of organic aerosol and soot emissions (II)

## ➢ Main combustion and burnout phase

- **Sufficiently high furnace temperatures and optimised mixing of the gases released from the wood logs with the combustion air**
  **➔ improved air supply geometries**

- **The excess air ratio should be kept at a rather constant and low level ($O_2$ concentrations of around 10 vol% d.b.) during the main combustion phase and also as long as possible during the burnout phase**
  **➔ implementation of advanced control concepts**

- **Implementation of appropriate air staging concepts (injection of tertiary air above the fuel bed) has shown to be a very efficient measure for emission reduction**

# Primary measures for low-dust emission stove concepts – reduction of organic aerosol and soot emissions (III)

## ➢ Optimisation tools

- **CFD simulations in order to optimise**
  - burning chamber geometries
  - distribution of window purge air
  - number and position of tertiary air nozzles as well as partitioning between the window purge air and the tertiary air flow
- **Experimental research**

## ➢ Expected impact

- **PM emission reduction to 20 to 25% (factor 4 to 5) of the emissions of old stoves**
- **PM emission reduction to about 50% (factor 2) of the emissions of present state-of-the-art stoves**

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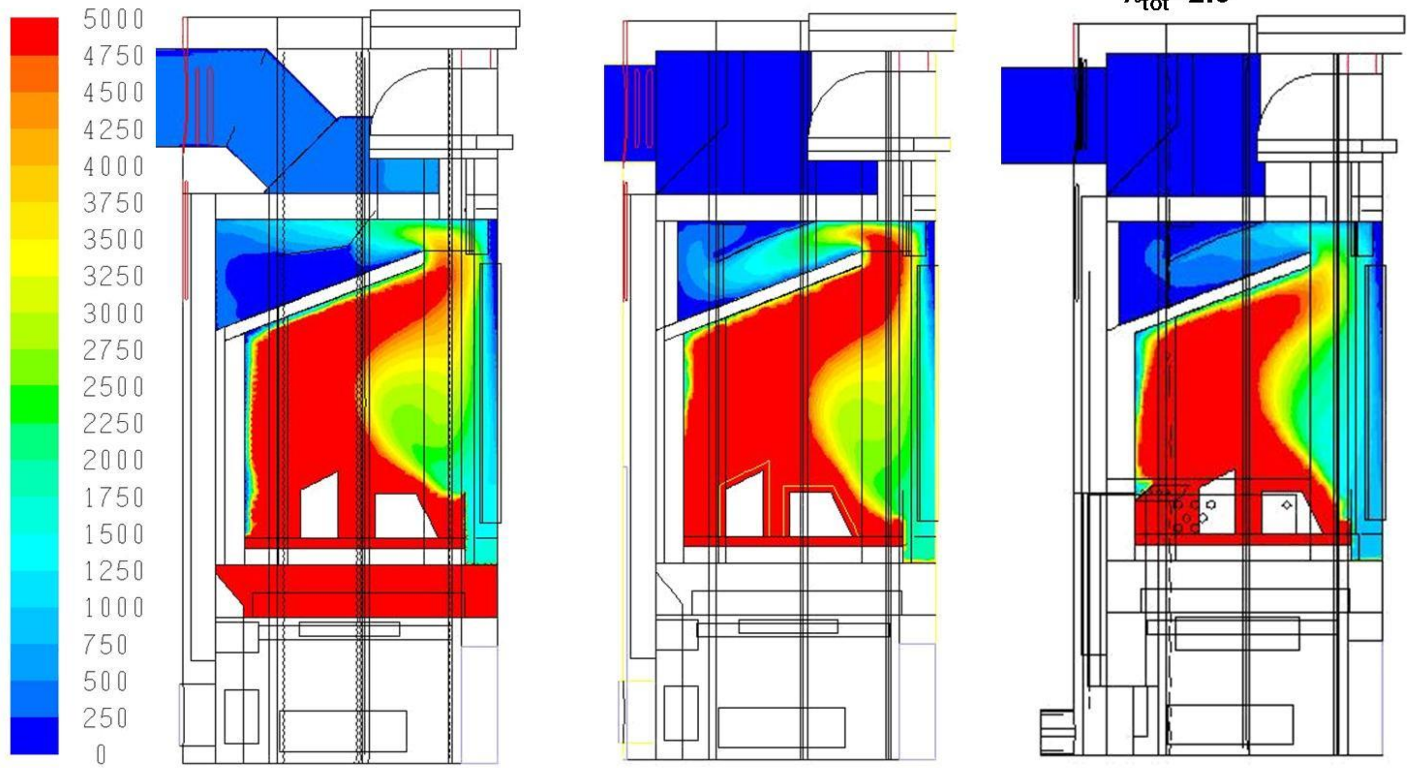
# Primary measures for low-dust emission stove concepts – reduction of organic aerosol and soot emissions: design study




Iso-surfaces of CO concentrations [ppmv] in the flue gas in the vertical symmetry plane of the stove
- pre-optimised geometry: optimised geometry of post combustion chamber
- optimised geometry: injection of tertiary air above the wood logs

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# Primary measures for low-dust emission boiler concepts – reduction of organic aerosol and soot emissions (I)

➢ **Avoid phases with incomplete combustion during transient operation phases and partial load operation**

- **Design furnace cooling concepts in a way that also during partial load operation sufficiently high temperatures are provided for an almost complete oxidation of soot particles and organic compounds.**
- **Design secondary air nozzles in a way that also during partial load operation sufficiently high air outlet velocities and mixing of the combustion air with the flue gas is provided.**
- **Implement process control measures (actuators, control strategy) which guarantee for appropriate air staging also during partial load operation.**

# Primary measures for low-dust emission boiler concepts – reduction of organic aerosol and soot emissions (II)

## ➢ Optimisation tools

- **CFD simulations in order to optimise**
  - Burning chamber geometries and cooling concepts
  - Number, position and orientation of secondary air nozzles
  - Air staging settings
    (distribution between primary and secondary combustion air)
- **Experimental research**

## ➢ Expected impact

- **PM emission reduction of the present state-of-the-art by up to 30% (related to whole day operation cycles including transient and stable operation conditions).**

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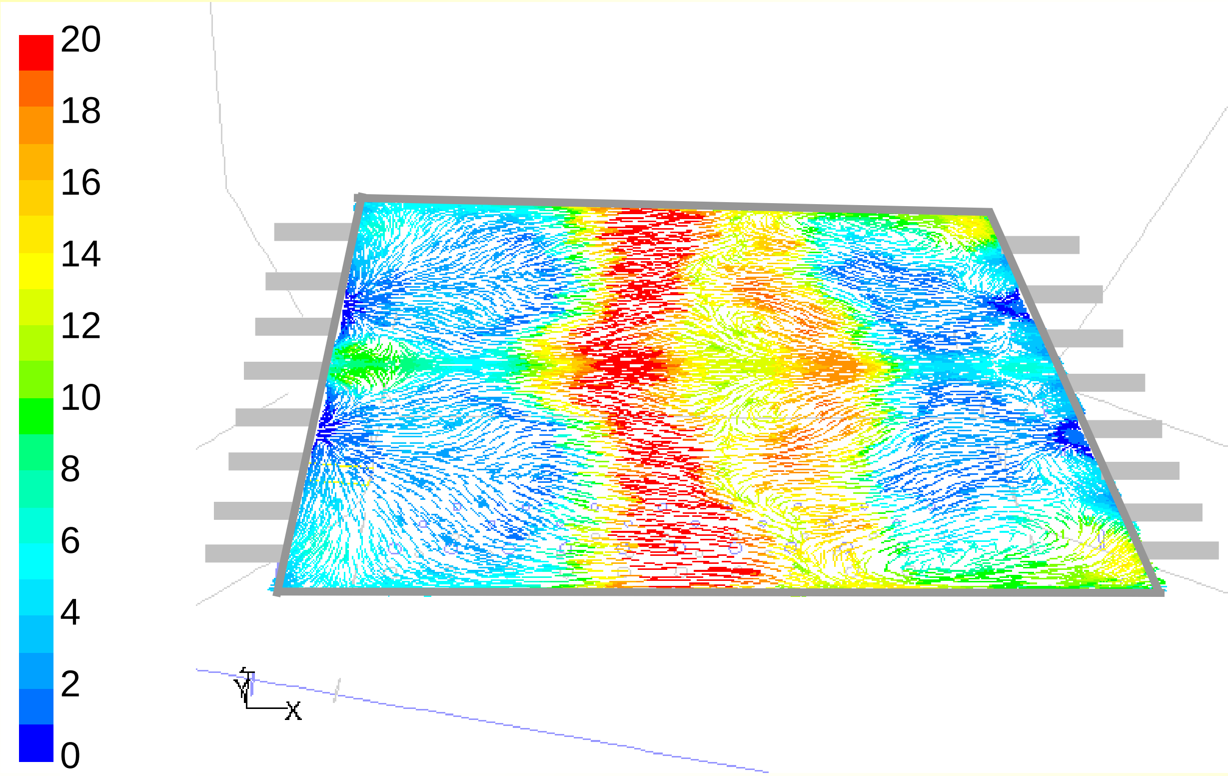
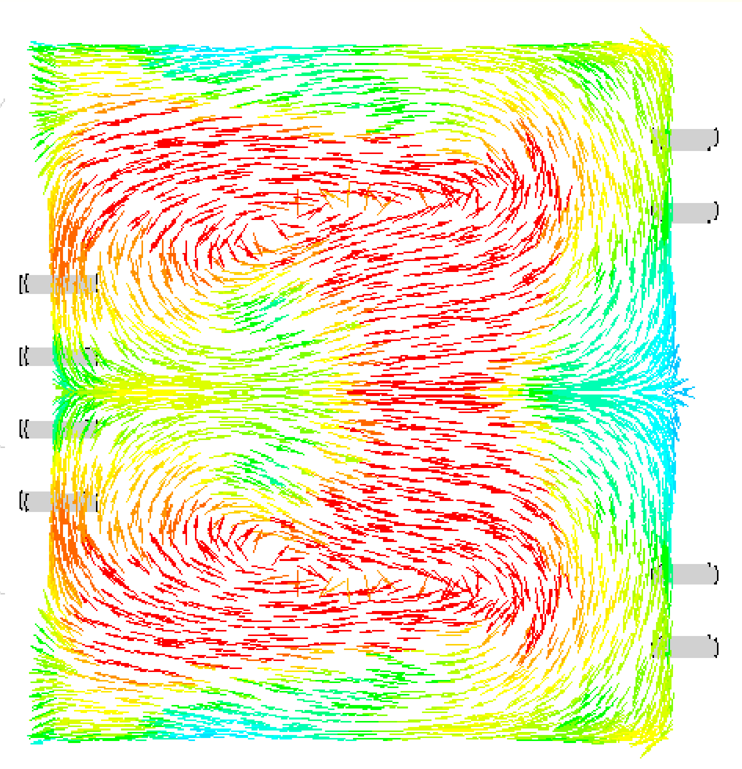
# Primary measures for low-dust emission boiler concepts – reduction of organic aerosol and soot: optimised secondary air injection

## Basic nozzle design

## Improved nozzle design



Flue gas velocity vectors [m/s] in a horizontal cross-section directly above the secondary air nozzles; simulations for full load operation

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# Primary measures for low-dust emission boiler concepts – reduction of inorganic aerosol emissions (I)

- During combustion of chemically untreated biomass K is the most relevant element regarding inorganic aerosol formation.
- Consequently the K content of a fuel, or in more detail, the K release from the fuel to the gas phase during combustion determines the amount of inorganic aerosols formed.
- Generally two possibilities exist to reduce the K release
  - chemical reactions of K with other ash forming elements and
  - reduced fuel bed temperatures

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# Primary measures for low-dust emission boiler concepts – reduction of inorganic aerosol emissions (II)

- With increasing amounts of Si and P in the fuel an enforced embedding of K in the bottom ashes can be observed.

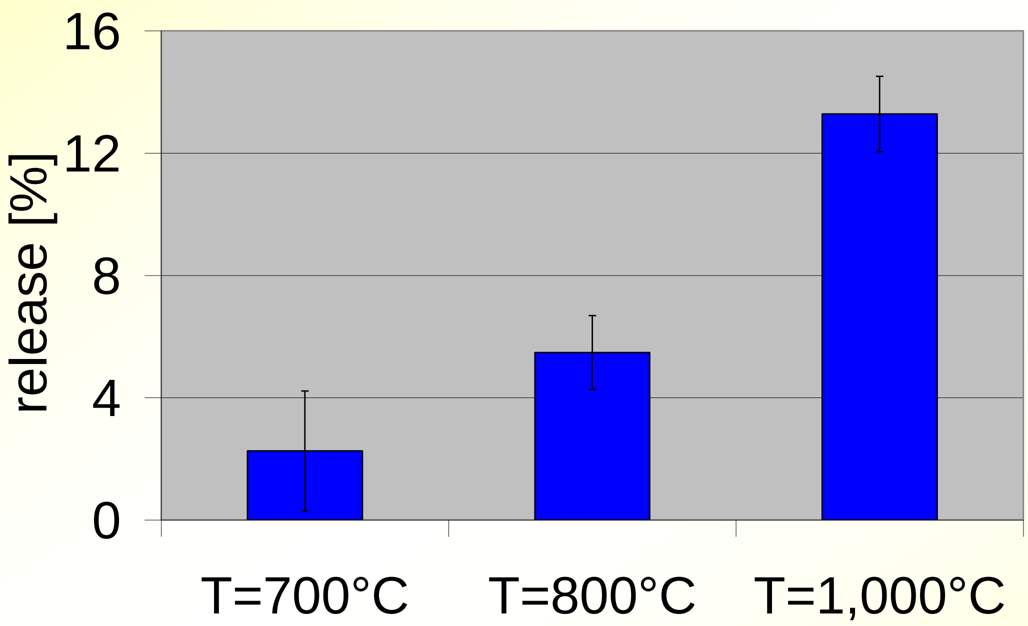
- Consequently, the application of these elements as K-catchers could be considered e.g. as fuel additives (for instance Kaoline, phosphates) or by fuel blending.

- Disadvantages:
  - Increased ash content
  - Si-K and P-K-rich phases show comparably low ash melting temperatures reaching ranges significantly below 1,000°C.

➔ The advantage of reduced K-release may be accompanied by higher efforts for de-ashing as well as slagging problems

# Primary measures for low-dust emission boiler concepts – reduction of inorganic aerosol emissions (II)

- **Element release from the fuel bed to the gas phase increases with rising fuel bed temperatures.**




**Release of K from the fuel to the gas phase during pellet charcoal combustion; results from test runs at a lab-scale reactor**

# Primary measures for low-dust emission boiler concepts – reduction of inorganic aerosol emissions (III)

## Optimisation tools

- **Application of additives**
- **“Cold operation” of the fuel bed**
  - by extremely staged combustion (primary air ratios <0.5)
  - by external cooling of the fuel bed

## Expected impact

- **Presuming an almost complete gas phase burnout (almost no organic aerosol and soot emissions), PM emissions below 3 mg/MJ can be achieved by these measures.**

# Conclusions (I)

- **Low-dust combustion concepts for small-scale biomass combustion systems must generally be divided into concepts for stoves and for boilers.**

- **For both types of systems:**
  **reduction of coarse fly ash emissions to almost zero emission level forms a first step which can be achieved by appropriate grate and furnace geometries as well as intelligent air staging.**

- **Low-dust technologies for stoves:**
  - **minimisation of organic aerosol and soot formation**
    - intelligent control of the burning rates during the ignition phase
    - introduction of staged combustion

➔**PM emissions can be reduced to 20 to 25% of the emissions of old stoves and to about 50% of the present state-of-the-art.**

# Conclusions (II)

## ➢ Low-dust technologies for boilers:

- **Minimisation of organic aerosol and soot emissions**
  - optimised burnout conditions during transient phases and partial load by appropriate burning chamber geometries and cooling concept
  - optimised secondary combustion air injection
  - appropriate process control systems which support the implementation of air staging

- **Reduction of inorganic aerosol emissions:**
  **the K-release from the fuel to the gas phase must be reduced**
  - application of additives (alkaline catchers – be aware of the increased ash content of the fuel and influences on the slagging behaviour)
  - concepts aiming at low fuel bed temperatures such as extreme air staging (very low primary air ratios).

➔ **Based on this approach PM emissions could be reduced to values below 20% of the present state-of-the-art (according to lab-scale tests)**

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