



bioenergy2020+



# Particulate matter emissions from small-scale biomass combustion systems – characterisation and primary measures for emission reduction

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## Background and objectives

- **FutureBioTec - Future low emission biomass combustion systems**
  - Project funded within ERA-NET Bioenergy
  - Duration: 36 months (1 October 2009 - 30 September 2012)
  - 9 scientific and 2 industrial partners from 8 European countries  
project coordinator: BIOENERGY 2020+, Graz, Austria
- The envisaged **increased use of renewable energy** as a measure for CO<sub>2</sub> emission abatement must be achieved **without increasing** other harmful emissions such as PM<sub>2.5</sub>, NO<sub>x</sub>, CO, OGC and PAH.
- Especially in the **small and medium-scale heating sector**, increased biomass utilisation must be accompanied by **further technology development** towards low emission combustion systems.
- *FutureBioTec* aimed to provide a substantial contribution concerning the development of **future low emission stoves** and **boiler systems** in the small and medium capacity range.



## Project partners

- BIOENERGY 2020+ GmbH, A
- Graz University of Technology, A
- University of Eastern Finland, FIN
- Technology and Support Centre in the Centre of Excellence for Renewable Resources, GER
- Teagasc, Crops Research Centre, IRL
- Institute of Power Engineering, P
- Umeå University, SWE
- Luleå University of Technology, SWE
- SP Technical Research Institute of Sweden, SWE
- Warma-Uunit Ltd., FIN
- Applied Plasma Physics AS, NOR



## Methodology

- **The work performed was based on the following approach**
  - **Literature surveys** as well as summary and **evaluation of data** already existing at the project partners in order to define the present state-of-the-art.
  - Dedicated **experimental work** performed under comparable conditions at different project partners.  
(defined based on the research need resulting from the state-of-the-art surveys)
  - **Evaluation of test runs** supported by the utilisation of **calculation / simulation tools** for process design, optimisation and evaluation.
  - **Compilation of guidelines.**



## Formation of PM emissions during biomass combustion

### ■ Coarse fly ash particles

- Entrainment of fuel, ash and charcoal particles from the fuel bed
- Emissions increase with increasing ash content of the fuel, load and gas flow through 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, ZnO etc.)
- Particle formation by nucleation and particle growth by condensation and coagulation

→ Strongly depend on the chemical composition of the fuel used

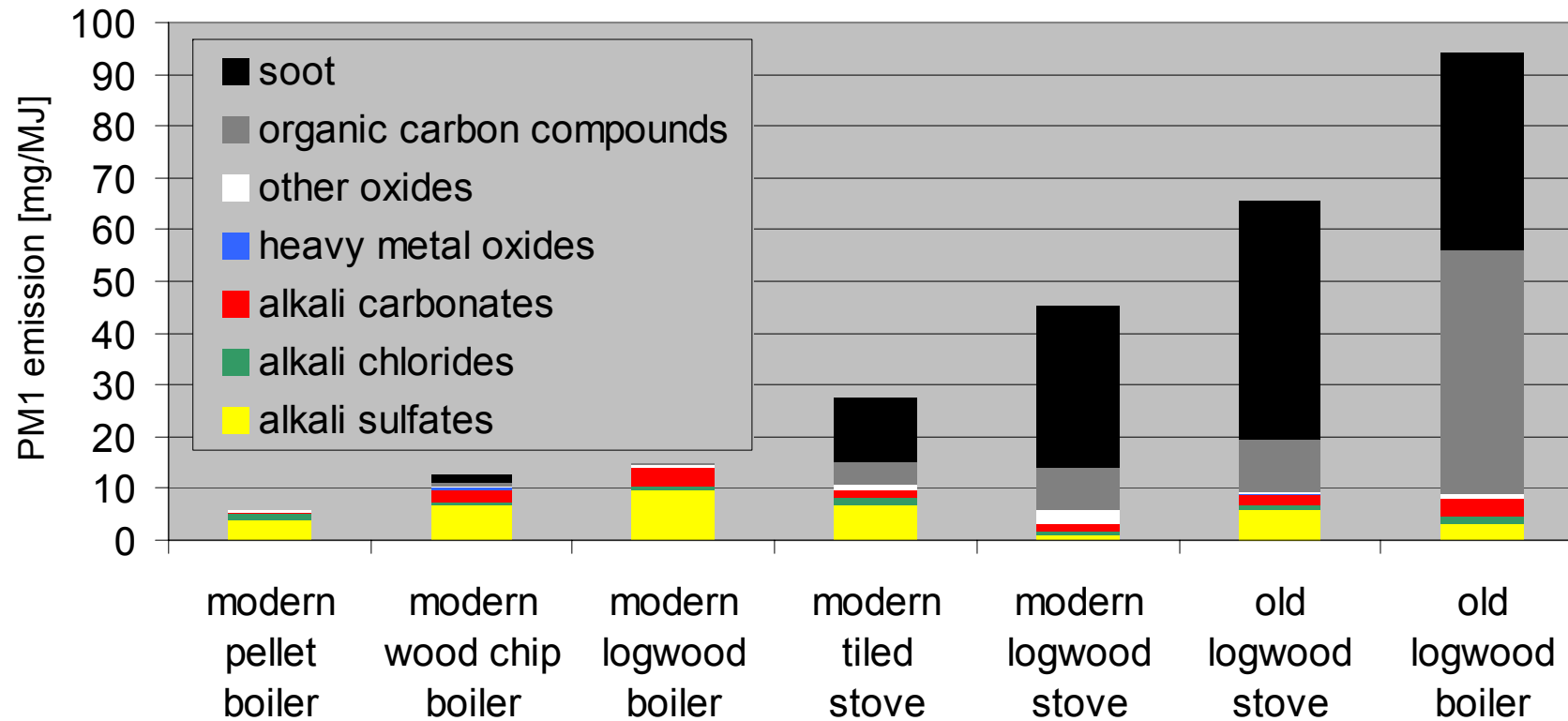
### ■ Carbon containing aerosols (excluding carbonates)

- Originate from incomplete combustion
- Distinguish between organic aerosols and soot

→ Can be avoided by achieving complete burnout



## Typical PM emissions from small-scale biomass combustion and their chemical composition



Results of analyses of PM<sub>1</sub> samples taken over whole day operation cycles from the respective systems

- **Stoves: reduction of organic aerosols and soot emissions**
- **Automatic boiler systems: reduction of inorganic aerosol formation**





## Primary measures for emission reduction (I)

- **Primary measures for PM emission reduction**
  - **Optimised burnout** → formation of organic aerosols and soot can be reduced to almost neglectable levels
  - **Low fuel bed temperatures** → reduction of inorganic aerosol formation due to reduced K release from the fuel to the gas phase
- **Appropriate air staging forms the basis for modern low-emission combustion concepts in all capacity ranges.**
- **Air staging means**
  - primary combustion air is supplied directly to the fuel bed
  - secondary combustion air is injected into the burnout zone
- **The overall excess air ratio ( $\lambda_{tot}$ ) should be kept as low as possible in order to achieve high efficiencies.**
- **False air intake should be minimised (since it cannot be controlled).**





## Primary measures for emission reduction (II)

- **The primary air ratio should be below 1**
  - higher amounts of secondary combustion air at the same  $\lambda_{\text{tot}}$ 
    - higher momentum of the secondary air → higher turbulence
  - reduced velocities of the combustion air in the fuel bed
    - less entrainment of fuel, charcoal and ash particles from the fuel bed
  - relevant basis also for  $\text{NO}_x$  emission reduction
- **Secondary combustion air injection**
  - Intensive mixing of the air with the flue gases
    - geometry of the combustion chamber
    - diameter and number of the secondary air injection nozzles
    - positioning and orientation of the secondary air injection nozzles
  - Avoid reverse flows of the air into the primary combustion chamber



## Primary measures for emission reduction (III)

- **Appropriate residence time**
  - **Primary combustion zone**
    - ➔ NO<sub>x</sub> emission reduction
  - **Secondary combustion zone**
    - ➔ enough residence time at high temperatures (>800°C) for almost complete burnout
  
- **Combustion chamber temperature resp. combustion chamber cooling**
  - **Primary combustion zone**
    - should be well isolated and not be cooled by water jackets
    - it can be cooled by surrounding secondary combustion air channels
  - **Secondary combustion zone**
    - moderate cooling possible
  - **For changing moisture contents: controlled and flexible cooling by flue gas recirculation is recommended**



## Primary measures for emission reduction (IV)

### ■ Other important aspects

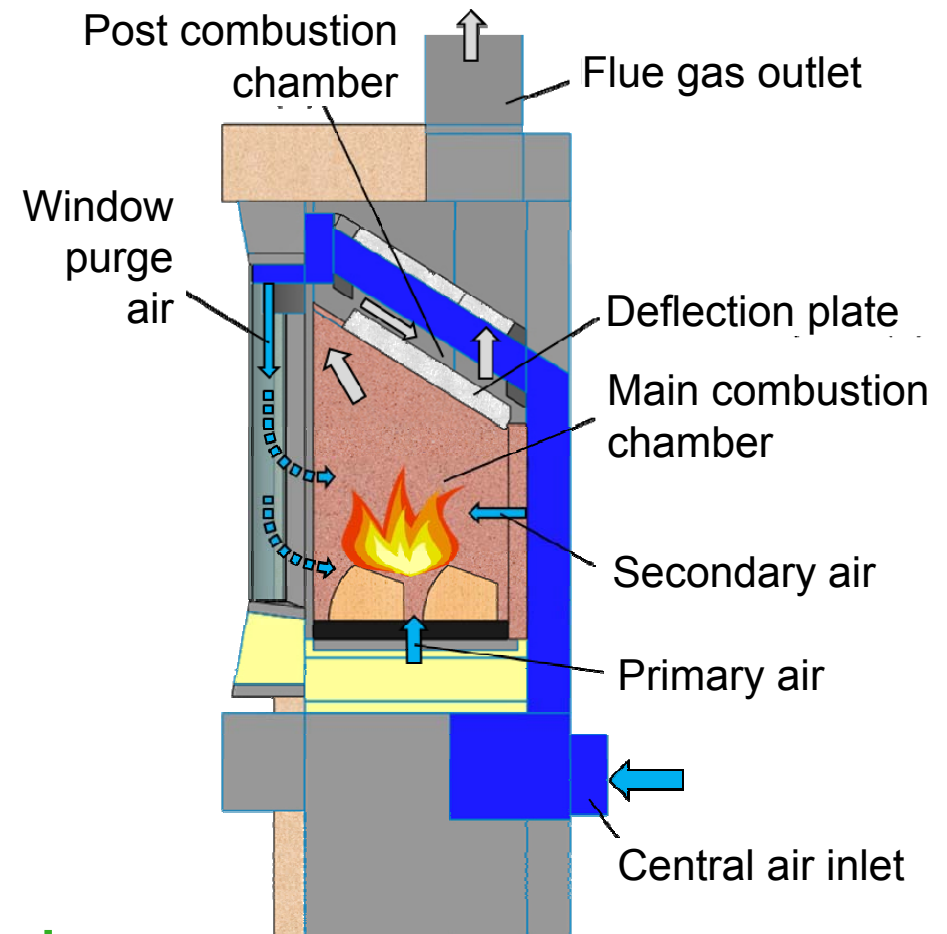
- Application of advanced **control systems**
  - temperature control in stoves
  - excess air ratio control in stoves and boilers
  - correct implementation of air staging in stoves and boilers
- Correct stove and boiler **dimensioning**
  - minimise stop-and-go operation of boilers
  - avoid partial load operation of stoves
- Application of **CFD simulations** as an efficient tool to
  - analyse different options how to implement primary measures
  - contribute to a significantly faster problem solution process
- Appropriate **user training** and information for stove users as an important primary measure to avoid operating errors



## Emission reduction in stoves – approach

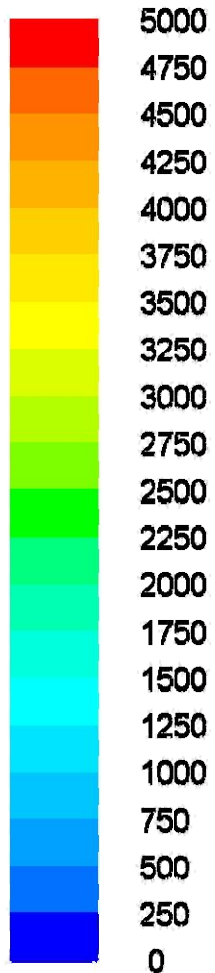
### ■ Stepwise implementation of the measures mentioned

- CFD-supported implementation of air staging (window purge air and secondary combustion air) and optimisation of the post combustion chamber
- Automated control system air supply control based on furnace temperature measurements
- Improved isolation of the main combustion chamber
- Compilation of a low emission operation manual for chimney stove users
- Compilation of guidelines for low emission chimney stove design

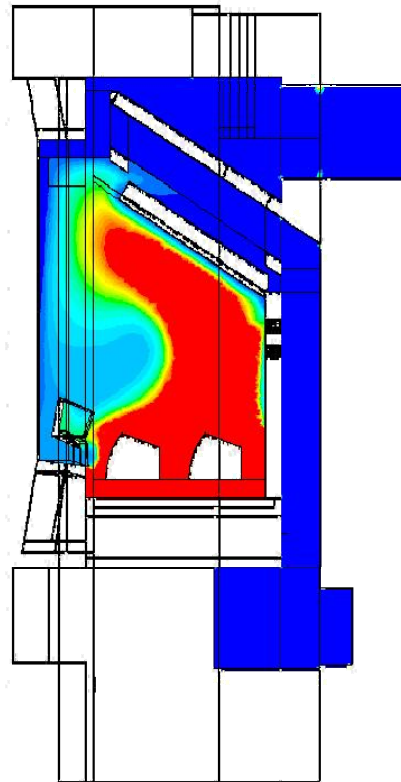




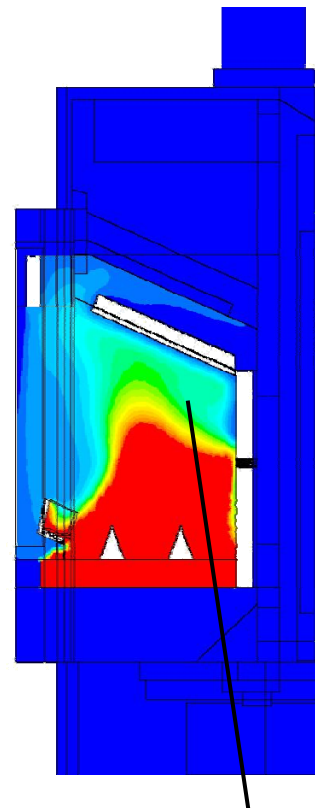
# Emission reduction in stoves – CFD-simulations – iso-surfaces of CO concentrations



20% secondary air  
80% window purge air



33% secondary air  
67% window purge air



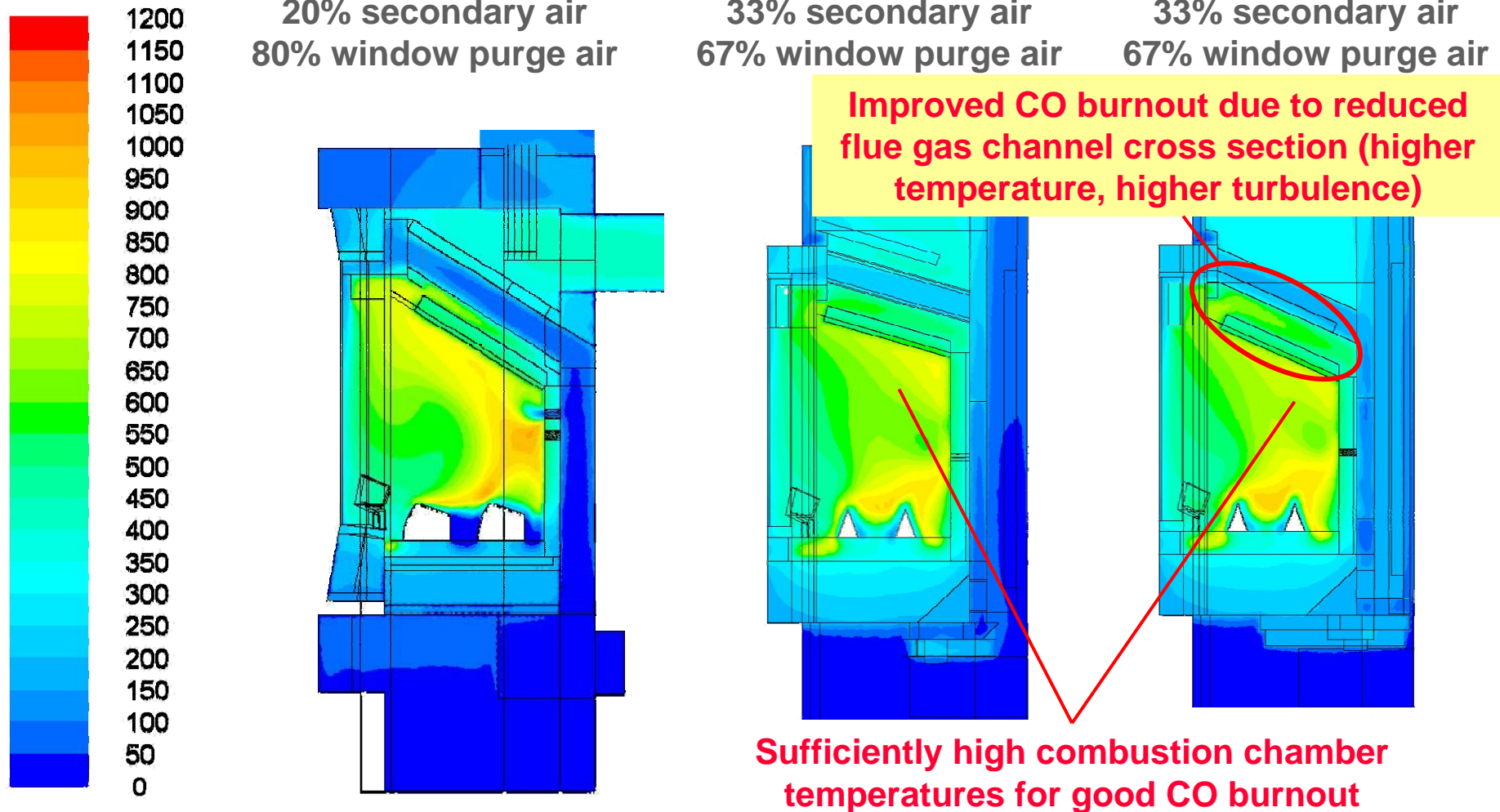
**Reduced CO concentrations due to sufficient secondary air**

**Strongly increased CO emissions without secondary air (not shown)**

- Implementation of secondary air injection
- Optimisation of the secondary air nozzle number and position
- Optimisation of the post combustion chamber



# Emission reduction in stoves – CFD-simulations – iso-surfaces of air, flue gas and stove temperatures



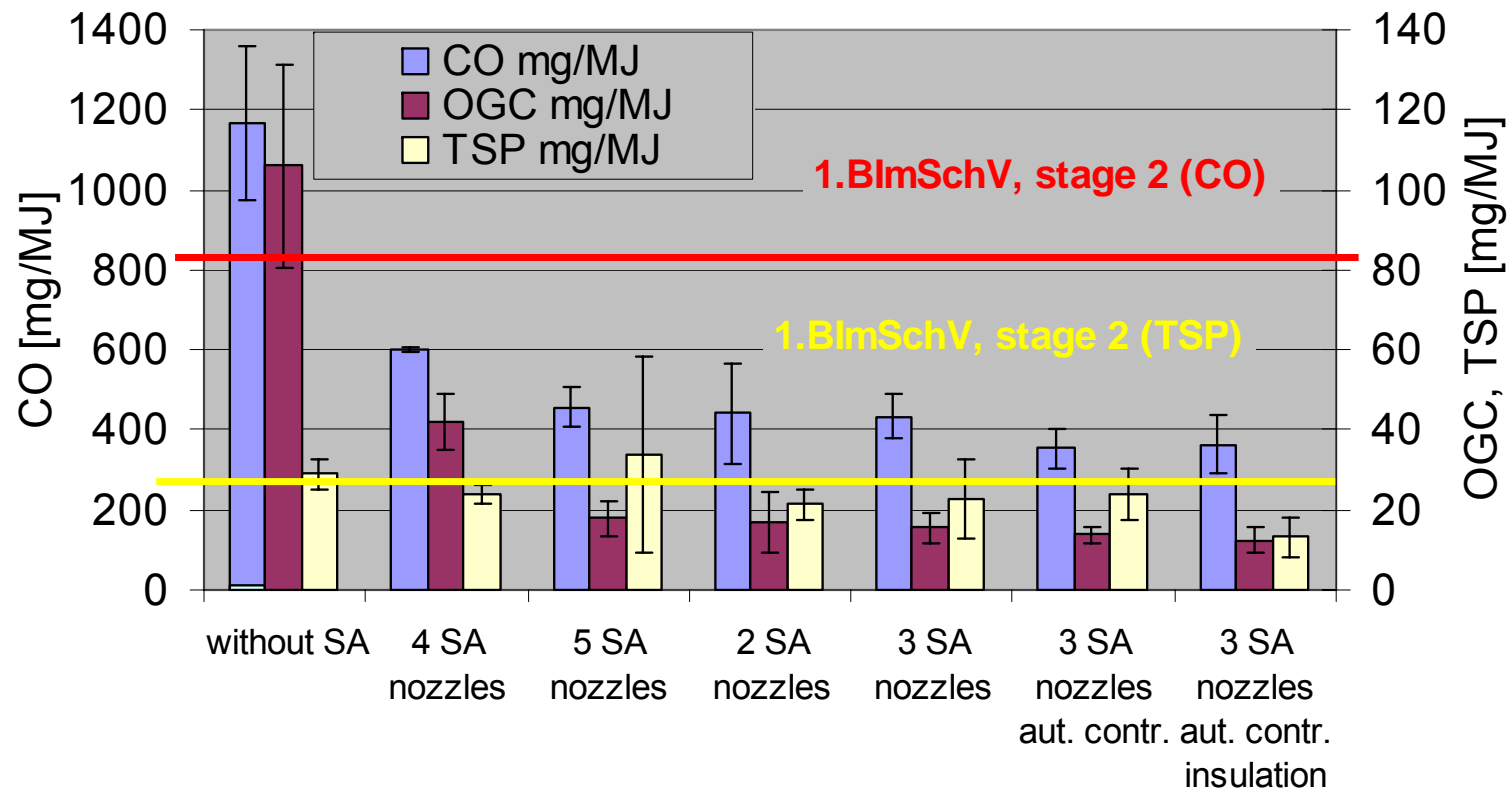
Iso-surfaces of air, flue gas and stove temperatures [°C] in the vertical symmetry plane of the stove





## Emission reduction in stoves – results

By the measures introduced a stepwise emission reduction could be achieved (CO: by 60%; OGC: by 86%; PM: by 55%)



SA ... secondary air injected from the back wall of the main combustion chamber  
 Mean values and standard deviations over batch 2, 3 and 4  
 aut. contr. .. with optimised automated control strategy





## Emission reduction in stoves – low emission operation manual for chimney stove users

### ■ Recommendations for **stove users** regarding low emission operation of chimney stoves were summarised. Some examples:

- **Ignition** should always be done from the top using proper fuel and ignition aid



- **Fuel:** moisture content should vary between 8 - 20 %, log diameter of 7-9 cm, small logs only for ignition, logs always shorter than firebox, wood briquettes according to class A1 in EN 14961-3, long briquettes should be broken due to volume increase during combustion, no pure bark briquettes due to smouldering conditions
- **Recharging strategies:** avoid overloading the stove, wrong placement of logs in firebox, recharge just after flame extinction



- **Air adjustments:** open all dampers during ignition, when recharging one should keep air through grate closed, all dampers should be closed when stove is out of operation

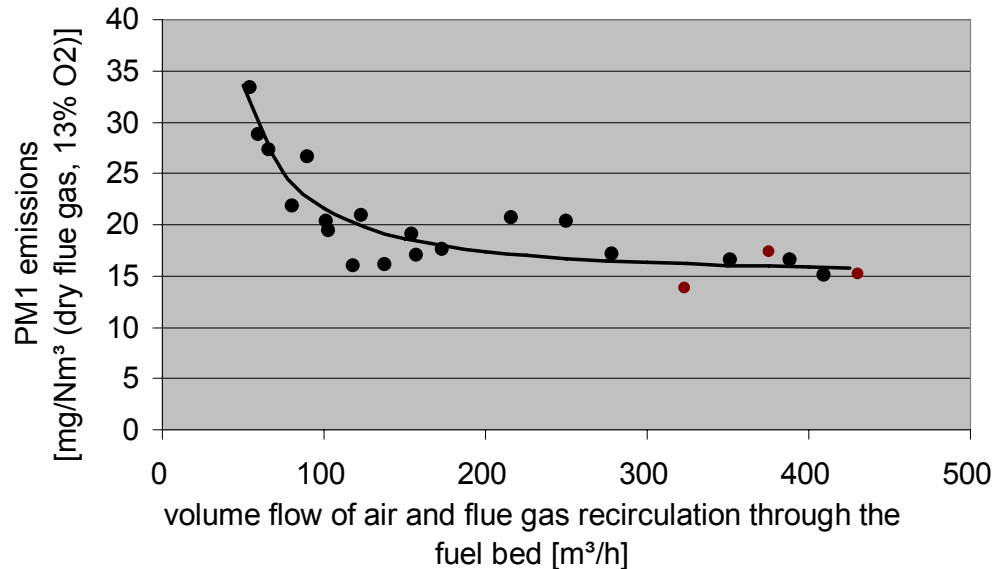


## Emission reduction in automated boilers – approach

- **Test runs with different fuels at different biomass grate combustion systems with hot water boilers**
  - **Combustion systems**
    - 180 kW horizontally moving grate technology
    - 40 kW grate fired boiler
    - 35 kW tilting grate
  - **Fuels**
    - conventional softwood chips and wood pellets
    - chipboard residues
    - agricultural fuels
- **Systematic investigations regarding the influence of the fuel composition, the air staging settings and flue gas recirculation on emissions (mainly PM and NO<sub>x</sub>)**



## Emission reduction in automated boilers – results regarding PM<sub>1</sub> emissions (I)

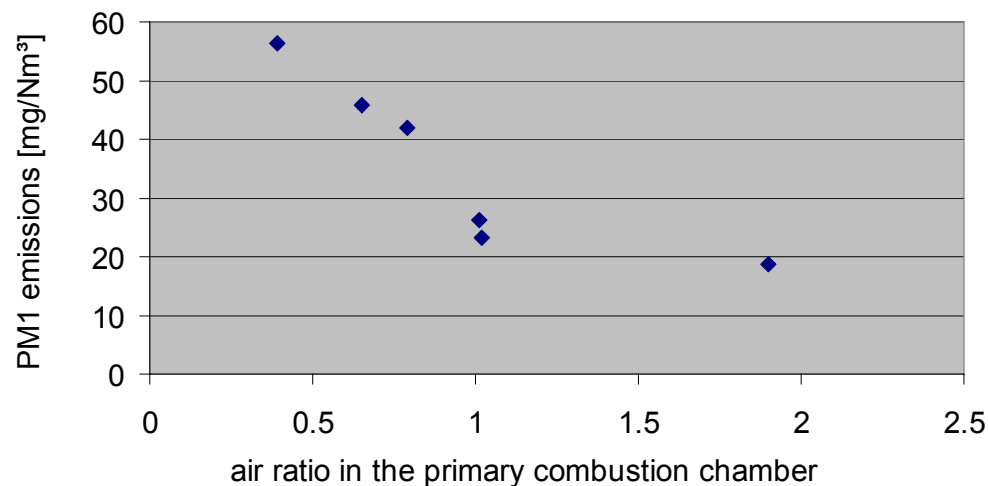


Horizontally moving grate (180 kW)

Fuel: chipboard

Temperature in the primary combustion chamber: 1,000°C

Line: regression for PM<sub>1</sub> emissions: the correlation is statistically highly significant



**Volume flow of the gas through the fuel bed causes a cooling effect  
→ decreases PM<sub>1</sub> emissions**

**Same effect for different grate technologies**

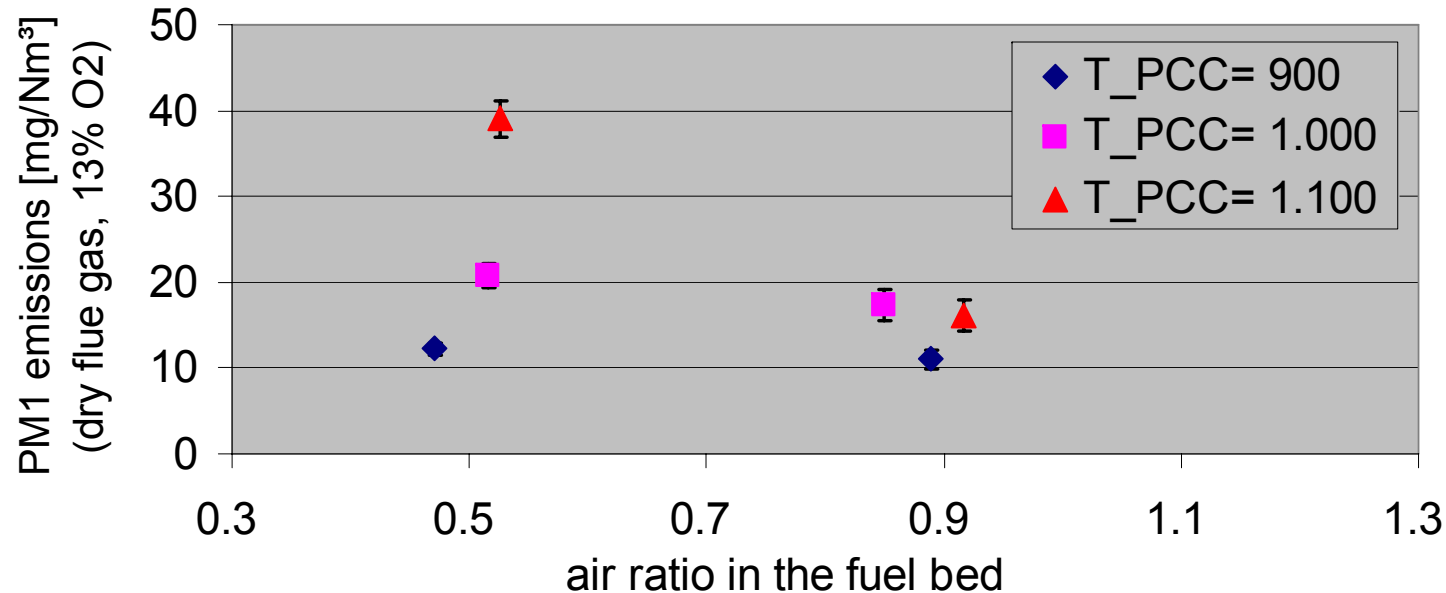
Moving grate with (40 kW)

Fuel: wood pellets

Temperature in the primary combustion chamber: 1,000°C



## Emission reduction in automated boilers – results regarding PM<sub>1</sub> emissions (II)



Fuel: chipboard, test runs performed at a 180 kW horizontally moving grate furnace;  
PCC primary combustion chamber

- With increasing temperatures in the primary combustion chamber the PM<sub>1</sub> emissions increase
- The effect is more pronounced at low primary air ratios



## Summary and conclusions (I)

- **Primary measures for emission reduction in stoves**  
(manually charged batchwise operated systems)
  - **Burnout optimisation** by
    - Correct implementation of air staging  
(window purge air and secondary combustion air)
    - Appropriate isolation of the main combustion chamber in order to achieve high combustion chamber temperatures
    - Development and implementation of automated control systems for air supply control
  - **PM emission reduction potential: up to 50%**  
(related to the present state-of-the-art)
  - **Appropriate user training and information** for stove users as an important primary measure to avoid operating errors



## Summary and conclusions (II)

- **Primary measures for PM emission reduction in boilers**  
(automatic boiler systems)
  - **Primary air ratio  $<1$**   
(to achieve low  $\text{NO}_x$  and low PM emission operation)
  - **Application of flue gas recirculation through the fuel bed**  
(reduce K release)
  - **Application of flue gas recirculation above the fuel bed in order to control the temperature in the primary combustion zone**
  - **With an intelligent combination of primary air and flue gas recirculation it is possible to control the volume flow through the fuel bed and the temperatures in the primary combustion chamber for a certain air ratio in the primary combustion zone**
  - **PM emission reduction potential: up to 50%**  
(at almost complete gas phase burnout)



## Summary and conclusions (III)

- Among other information about *FutureBioTec* especially the guidelines dealing with **low emission biomass combustion** can be downloaded from [www.bioenergy2020.eu](http://www.bioenergy2020.eu)
  - Low emission operation manual for chimney stove users
  - Guidelines for low emission chimney stove design
  - Design and operation concepts for low-emission biomass grate furnaces based on advanced air staging





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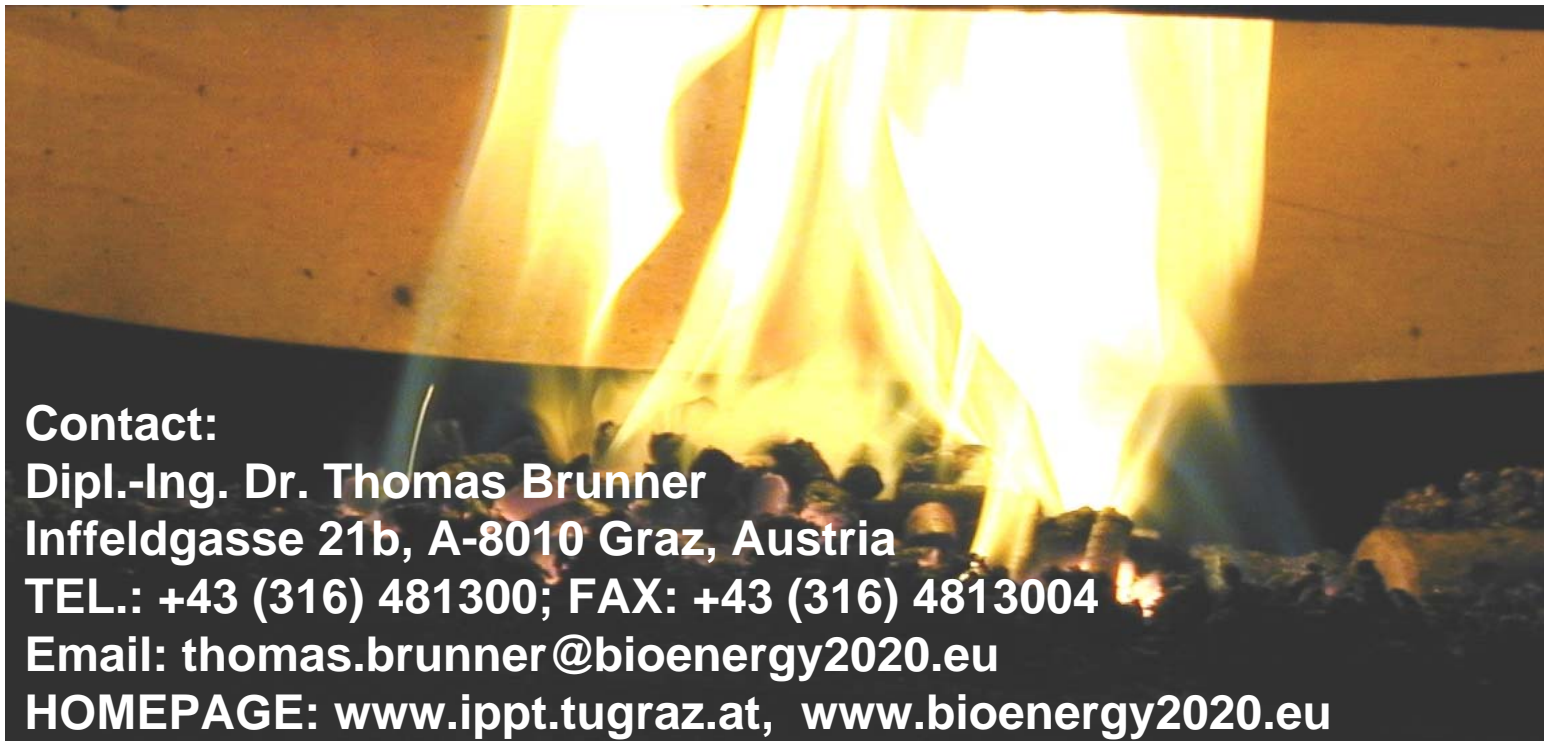


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***Thank you for your attention***



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