Biomass Combustion and Cofiring

IEA Bioenergy Task 32

Guidelines and relevant issues for stove development

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Introduction (I)

- Chimney stoves are one of the most common appliances used for residential heating in Europe.

- Apart from their use for heating purposes, stoves have recently become decorative accessories, and therefore a broad range of different designs are available nowadays.

- Within the scope of several national and international R&D projects primary measures for lowering emissions of wood stoves were evaluated on the basis of literature data as well as test runs with appropriately adapted stoves.

- Based on the results the guidelines presented has been worked out, which suggests primary measures regarding the design and process control for logwood stoves as a tool to considerably reduce emissions and increase efficiencies.

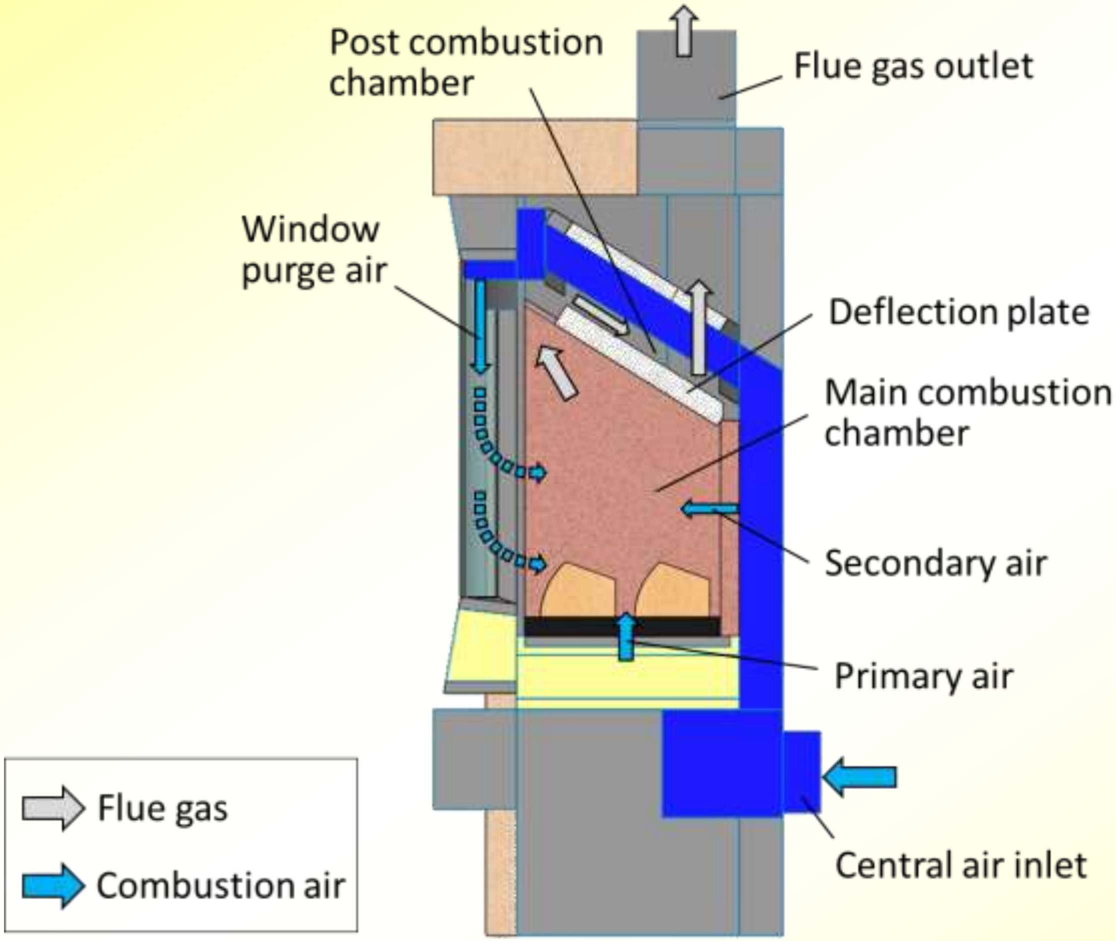
- Besides these guidelines also existing guidelines regarding suitable fuel qualities and stove operation shall be considered.

Introduction (II)

- **The design concepts for low-emission wood stoves presented in the following are applicable to**
  - **appliances that have a closed fire box**
  - **typical stove models**
  - **stoves using the updraft combustion principle**
- **These guidelines are not applicable to**
  - **heat storing appliances**
  - **sauna stoves**
  - **pellet stoves**
  - **cooking stoves**
  - **stoves with water jackets**
  - **stoves which apply the downdraft principle**

Logwood stove concepts – basic definitions

Schematic picture of a chimney stove

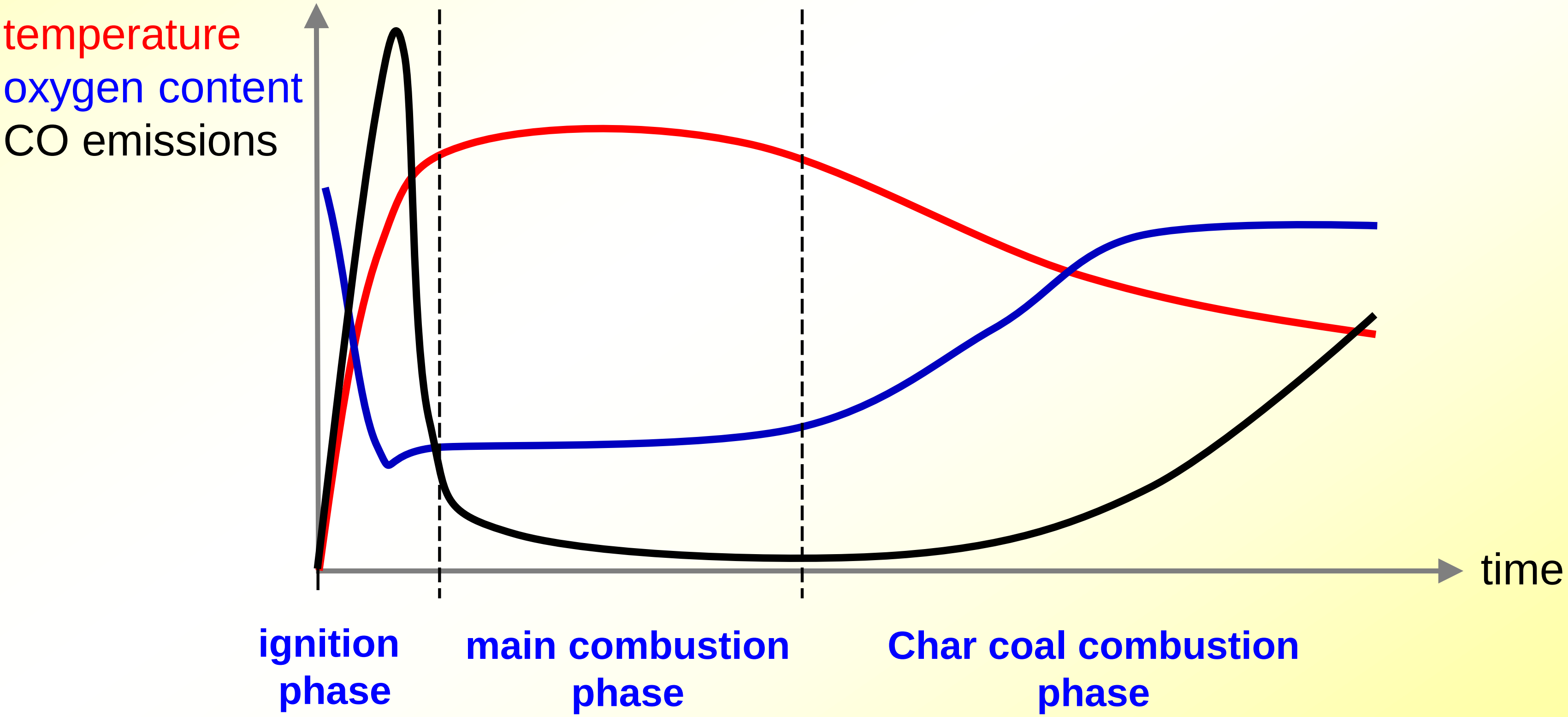


- **Main combustion chamber**
  - Fuel decomposition and the majority of the combustion reactions take place
  - Fuel zone (zone above the grate where the wood logs are positioned)
  - Secondary combustion zone where the gasification products and intermediate products from the fuel zone are burned
- **Post combustion chamber**
  - Zone where the combustion gases and particles burn out
- **Chimney draught**
  - Underpressure in the duct at the flue gas outlet

Logwood stove concepts – basic definitions

- **The batch wise combustion in stoves with its different phases and phase transitions represents the major challenge for a low emissions concept**

simplified scheme of a combustion batch in a logwood stove



Parameters affecting the emissions – particulate emissions

- **Fine particles (PM_1 = particles <1 µm aerodynamic diameter)**
  - **Soot**
    - formed in the flame due to incomplete combustion (not enough oxygen available) or due to cold surfaces

    → can be reduced by improved combustion chamber design and air staging
  - **Organic particulate matter**
    - formed due to incomplete oxidation of the combustion gases during secondary combustion and later condensation of gaseous organic compounds during the cooling of the flue gas

    → can be reduced by measures which improve the gas phase burnout
  - **Fine fly ash (inorganic particles)**
    - Formed by vaporization and nucleation/condensation of inorganic vapours (mainly K-vapours) released during combustion
- **Coarse particles (particles >1 µm)**
  - **Unburned fuel and ash particles entrained from the fuel bed**
    - Coarse particle emissions are affected by the air flow through the grate and length and shape of the ducts

    → can be reduced by low gas velocities in and around the fuel bed and by appropriate design of the combustion chamber

Parameters affecting the emissions – CO, OGC, PAH and NO_x emissions

- CO = carbon monoxide
  - intermediate product from the oxidation of carbonaceous material
  - effective monitoring parameter to evaluate burnout quality
  - highest typically during the ignition and the char coal burnout phase

- OGC = organic gaseous carbon compounds
  - OGC is released from the fuel during combustion
  - products of incomplete combustion
  - emissions mainly occur during the ignition and the main combustion phase

- PAHs = polycyclic aromatic hydrocarbons
  - environmentally highly relevant
  - products of incomplete combustion

- NO_X = nitrogen oxides
  - emissions from wood combustion are mainly fuel derived
  - NO_X emission level is mainly determined by the nitrogen content in the fuel

General requirements for low emission chimney stoves (I)

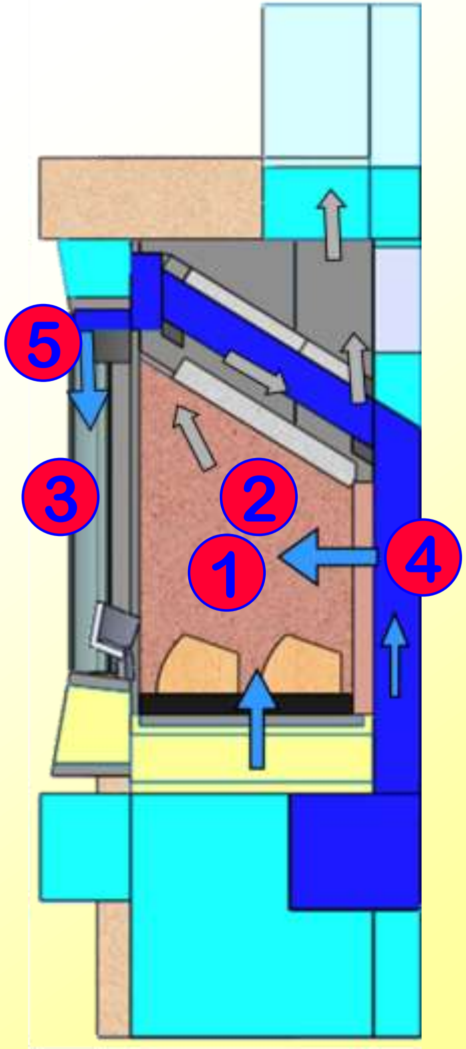
Adequate amount of combustion air

- Sufficient but not too high draught is needed
- Typical draught variations in chimneys and associated variations of the combustion air flows shall be considered during stove development or by appropriate measures

Enough residence time at high flue gas temperatures

- As high as possible temperatures are a pre-requisite for the oxidisation of products from logwood gasification.
- Therefore, the temperature in the main and the post combustion chamber should be kept as high as possible
- The temperatures are affected by:

1. Refractory lining in the main combustion chamber
2. The shape and size of the main combustion chamber
3. Window material & size
4. Location of air nozzles for secondary air injection
5. Window purge air injection strategy

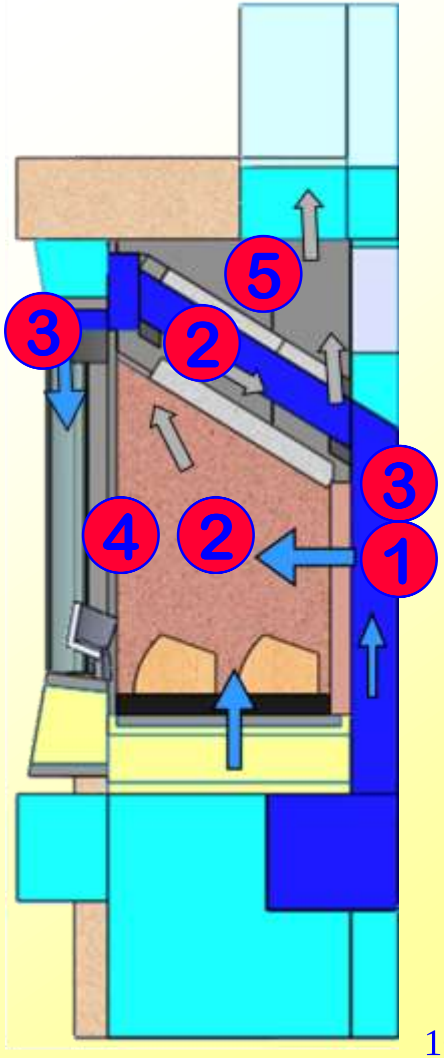


General requirements for low emission chimney stoves (II)

➢ Mixing of the flue gases with the combustion air

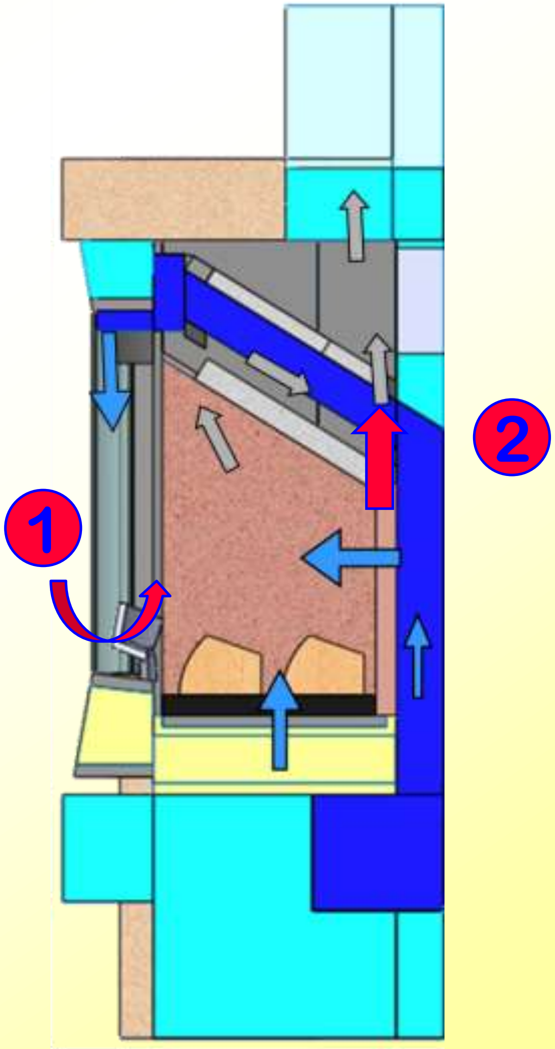
- **Is needed to achieve complete combustion**
- **Mixing is affected by**

1. The direction and geometry of the air nozzles
2. The velocities of the flue gas and combustion air
3. The distribution of different air flows, such as secondary air and window purge air (air staging)
4. The geometry of the main combustion chamber
5. The use of baffles in the post combustion chamber



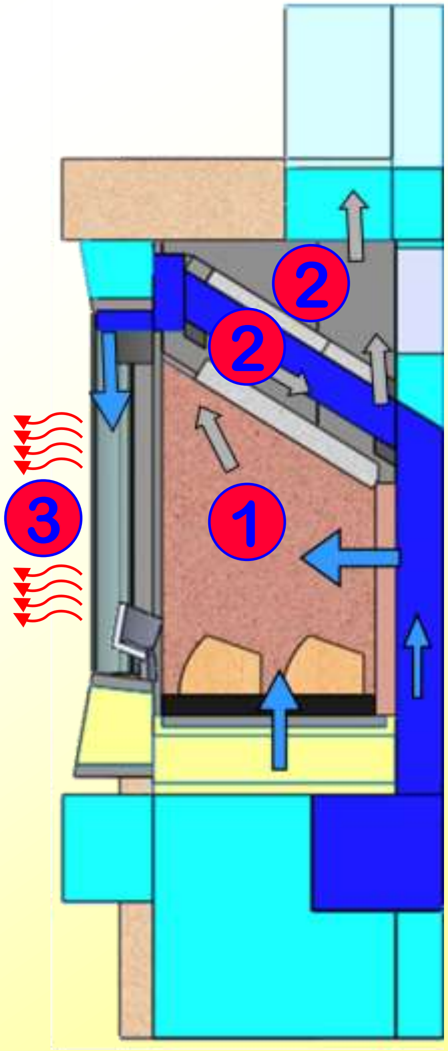
General requirements for low emission chimney stoves (III)

- **Leakage air should be avoided by using appropriate materials for the door and sealing of the door (1)**
- **Short-circuiting of the flue gases should be avoided**
  - **No gaps between the plate separating the main combustion chamber from the post combustion chamber**
  - **Through such gaps unburned gases from the main combustion chamber could flow to the flue gas outlet without passing through the burnout zones in the main combustion chamber (2)**



Geometric design concept (I)

- **A logwood stove should consist at least of**
  - a **main combustion chamber (1)** and
  - a **post combustion chamber (2)**
- **The combustion chamber should be hot enough but the fuel bed should be kept at moderate temperatures**
- **Insulation materials should be used around the main combustion chamber to keep the combustion temperatures high**
  - **for example refractory bricks with heat resistant wool and a small air volume between insulation and the outer stove casting**
- **Radiation losses through the door shall be kept low (3)**
  - **window in moderate size**
  - **glass qualities with low radiation coefficient**
  - **double glazed windows (with an air gap)**

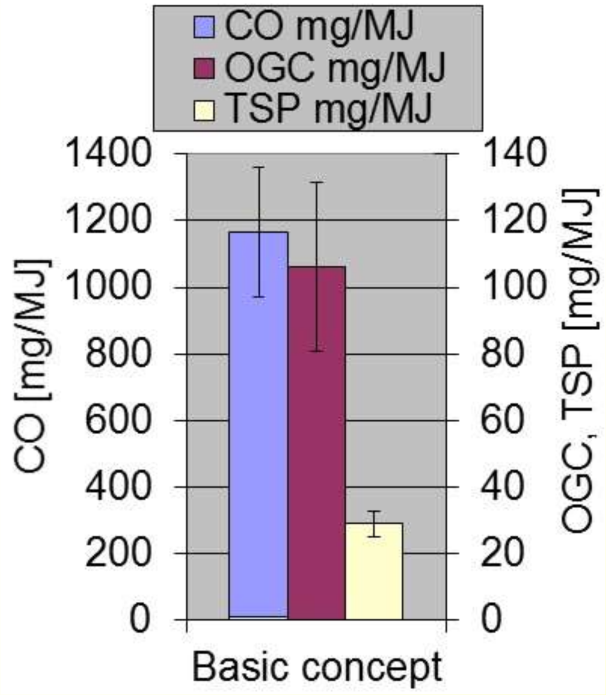


Geometric design concept (II)

- **The flue gas should have enough time to efficiently cool down downstream of the combustion chamber**
  - **Sufficient heat exchanging surfaces to maximize the efficiency**
    - should be associated mainly with the post combustion chamber
    - the heat exchange can be improved by introducing forced ventilation
- **A grate should be used**
  - **Simple de-ashing**
  - **Controlled primary air supply through grate is possible**
  - **However, air flow through the grate should be able to be shut down completely**
    - only kept open during the first ignition phase and during the last batch after flame extinction
- **Firebox geometry:**
  - **High and slim combustion chambers are preferable (compared to wide and low)**
    - this shape improves flame dispersion
    - it leads to a more homogeneous residence pattern for the pyrolysis gases produced in the hot zones and therefore less danger of streak-formation (short circuit flows to the exhaust pipe)

Example from practise – Step 1 – optimised basic stove concept

- **According to the design recommendations discussed, a stove has been designed, constructed and tested.**
  - **Sufficiently large main combustion chamber**
  - **CFD-optimised combustion chamber geometries**
  - **Primary and window purge air separately controllable**
  - **Appropriate insulation of the glass door and the main combustion chamber**
- **Following these guidelines within test runs a good performance regarding low emission combustion could be achieved for several stoves**



Explanations:

OGC … organic gaseous compounds

TSP … total suspended particulate matter = total dust = coarse fly ash + PM_1

MJ related to the NCV of the fuel

Mean values and standard deviations of averaged emissions over entire batches (from closing the door until opening it again for recharging)

Air supply and air staging (I)

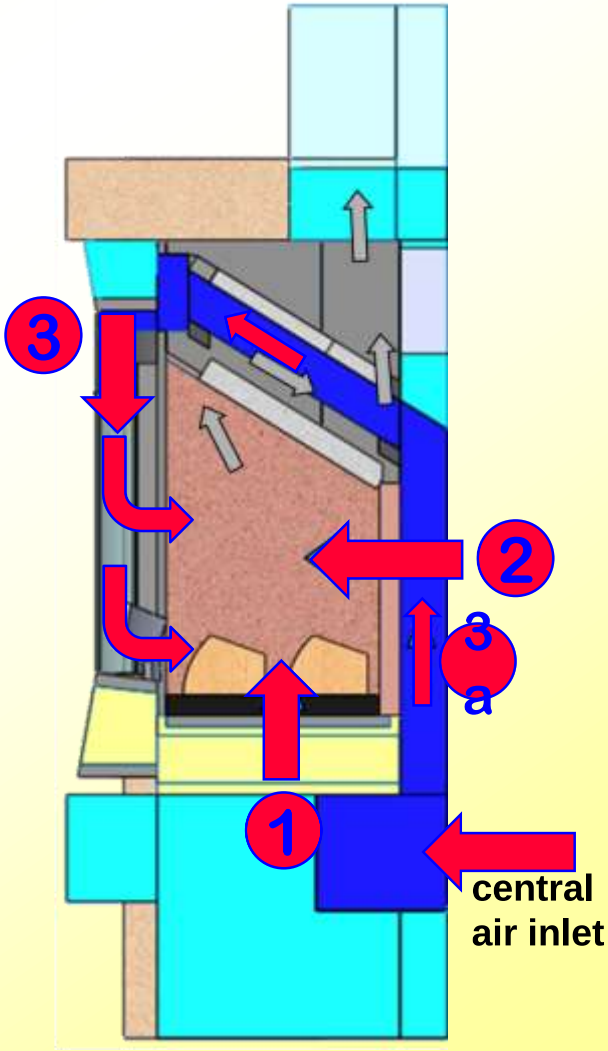
- **Air staging generally is an effective way of reducing the emissions in biomass combustion processes.**

- **Air staging means that different independently adjustable air flows are introduced to facilitate**
  - **optimized fuel decomposition**
  - **high degree of char burnout**
  - **an almost complete gas phase burnout**

Air supply and air staging (II)

➢ Combustion air can be supplied as primary, secondary and window purge air

- **Primary air (1)**
  - supplied directly to the fuel bed either from below the grate or at the bottom of the combustion chamber (if there is no grate)
  - mainly used during the ignition phase
- **Secondary air (2)**
  - supplied above the grate
  - should improve the oxidation of the gases released from the wood logs
- **Window purge air (3)**
  - can be pre-heated by flowing along the combustion chamber (3a)
  - mainly creates a flush air for the window to keep it clean from soot and tar deposits
  - it is recommended to introduce it only from the top of the door so that it flows downwards along the window
  - if appropriately designed the window purge air can contribute as primary and secondary air to the combustion process



Air supply and staging (II)

Minimum requirements

- **Primary air and window purge air**
- **They should be separately controllable**
- **Manual control should be achieved by a single hand gear (to avoid false operation)**

Injection of secondary air is strongly recommended

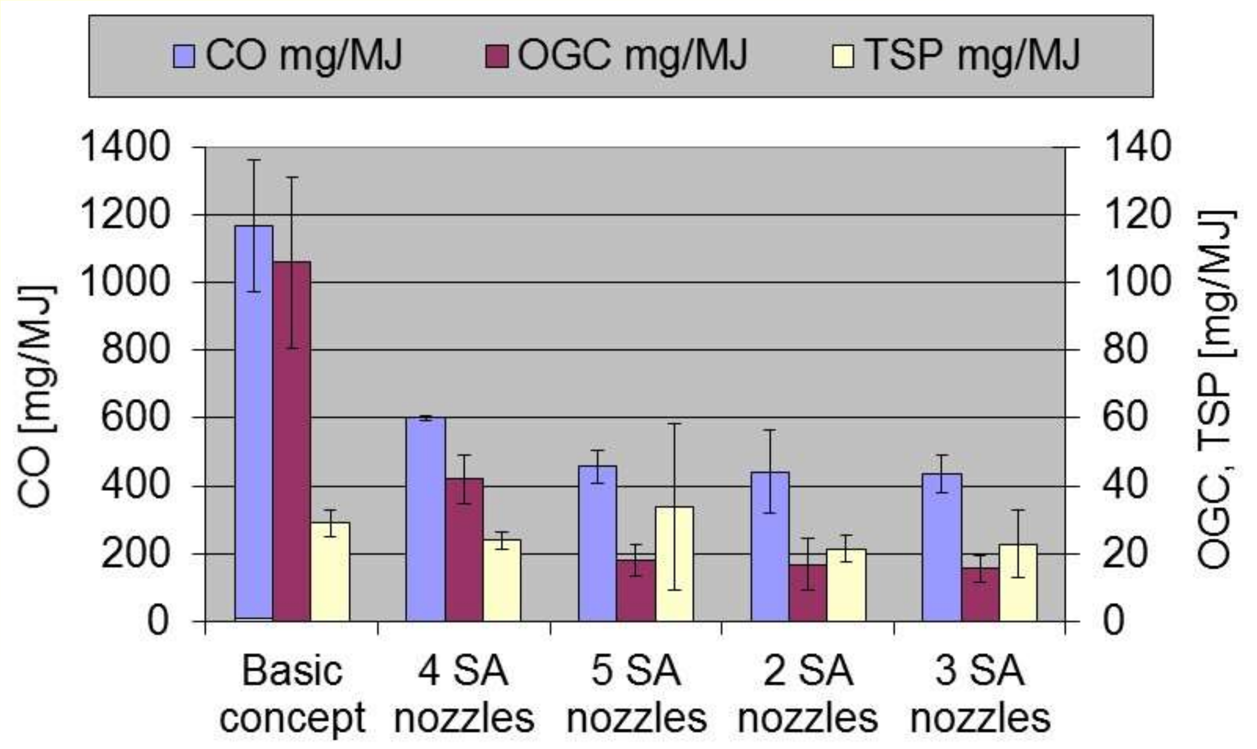
Other points of air staging design

- **Secondary and tertiary air should be pre-heated**
  (flow along the combustion chamber walls before injection)
- **Primary air should not be pre-heated**
- **Even distribution of window purge air**
- **Pressure drop should be kept low due to typically limited draught**
- **Correct positioning of the secondary air nozzles is important**
  - too low nozzles: secondary air can act as primary combustion air (increases fuel conversion)
  - too high: too late mixing of air and flue gases is achieved

Example from practise – Step 2 – optimised air staging

➢ The basic concept was supplemented with air staging

- Different numbers of secondary air nozzles have been tested
- An optimised design and positioning of the nozzles is important
- A significant emission reduction due to the air staging could be achieved



Explanations:

SA … secondary air
OGC … organic gaseous compounds
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Automatic combustion control (I)

- **Common logwood stove concepts are manually controlled. Therefore, process control efforts are usually limited to a change of the combustion air distribution at the end of the ignition phase.**
- **Advantages of an automated combustion control**
  - **reduces the user influences (operating errors)**
  - **provides the possibility to react on the changing process conditions throughout the entire batch**
- **Technical solutions**
  - **thermo-mechanical operated primary air flap**
    - simplest way but with restricted accuracy and effects
  - **electronic sensor driven automatic control**
    - more efficient but also more costly
    - the temperature (for example in the post combustion chamber) or the oxygen concentration of the flue gas can be applied as guiding parameters for automated adjustments of the combustion air flow and combustion air distribution by flaps; in future maybe also combined CO/O2 sensors may be used

Automatic combustion control – Example: temperature guided control of the combustion air supply (I)

➢ Concept

- **Temperature sensors are the cheapest sensors available and quite robust**
- **The combustion air flows (primary, secondary and window purge air) can be easily controlled by dampers**
  → temperature controlled combustion air supply

➢ Control strategy

- **Ignition phase**
  - Mainly primary air and a low amount of window purge air is injected in order to facilitate a quick ignition and rapid increase of the combustion chamber temperatures
- **Transition to main combustion phase**
  - As soon as temperature exceeds a certain level the primary air damper is closed to avoid excessive burning rates
  - At the same time secondary air and window purge air flows are increased to maintain adequate combustion air supply
  - During the main combustion phase the secondary and window purge air flow should kept constant. The distribution between these two flows depends on the furnace design (combustion chamber and air injection nozzle geometries) and must be experimentally optimised for a specific stove type.

Automatic combustion control – Example: temperature guided control of the combustion air supply (II)

Control strategy (cont.)

- **Transition to char coal burnout and char coal burnout phase**
  - when the furnace temperature starts to drop below a certain value, the amount of secondary and window purge air should be reduced to keep the temperature at a reasonably high and nearly constant value until the end of the batch
  - Thereby, excess oxygen is kept low and too much cooling of the combustion chamber is prevented

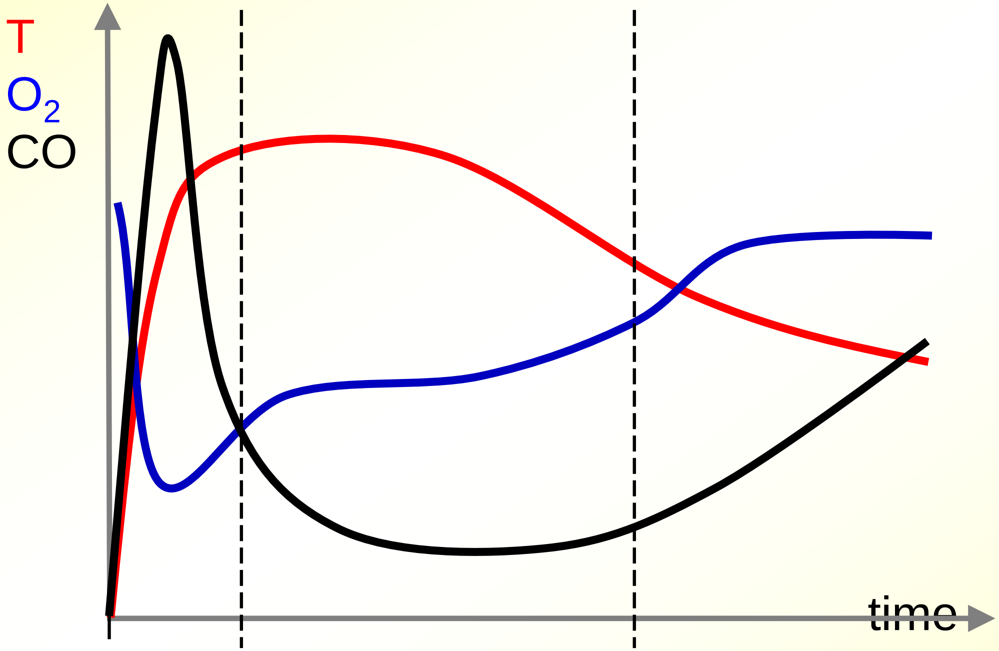
Effect

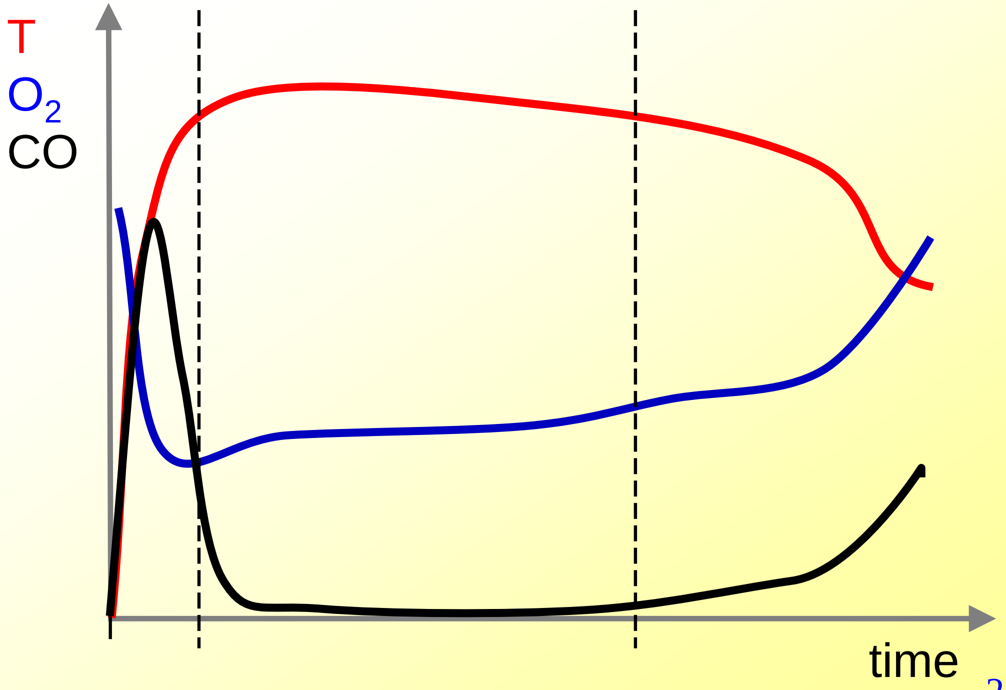
- **Shorter ignition phase**
- **With combustion air flow control during the main combustion and burnout phase more stable O_2 concentrations in the flue gas can be achieved**
- **Generally lower O_2 levels as well as sufficiently high temperatures can be achieved**

➔ **Lower emissions and higher efficiencies result**

Automatic combustion control – Example: temperature guided control of the combustion air supply (III)

- **Conventional uncontrolled stove: scheme of a combustion batch**
- **Automatically controlled stove: scheme of a combustion batch**
  - shorter ignition phase
  - higher temperatures
  - lower emissions
  - lower average O_2 content in the flue gas

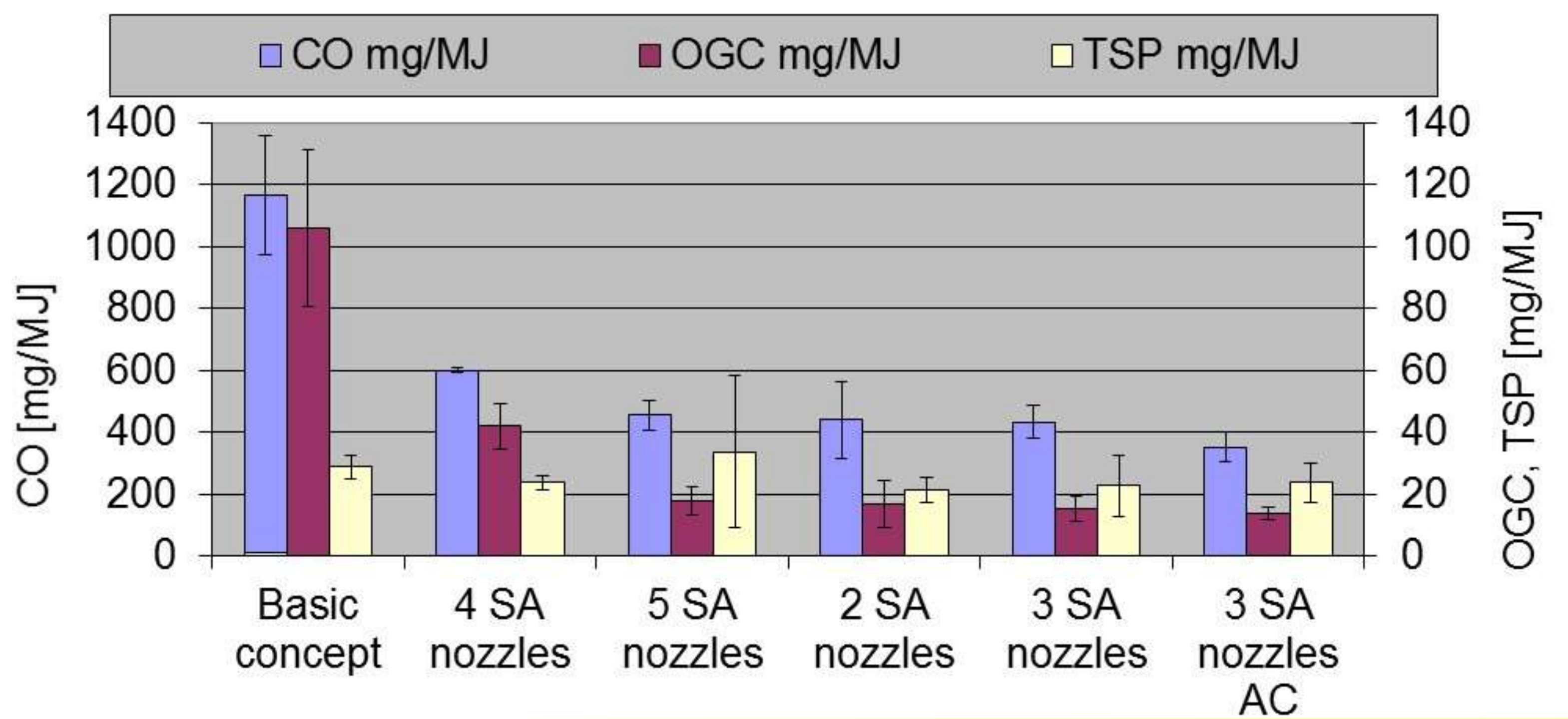




Example from practise – Step 3 – implementation of an automated control system

➢ **An automated control system as described before has been installed**

- **Further reduction of gaseous emissions**
- **Lower standard deviations regarding OGC and TSP**
- **Minimisation of user induced errors**



Explanations: SA … secondary air; AC … automated control; OGC … organic gaseous compounds; TSP … total suspended particulate matter; MJ related to the NCV of the fuel; mean values and standard deviations of averaged emissions over entire batches (from closing the door until opening the door again for recharging)

CFD-aided design of wood stoves

- CFD (computational fluid dynamics) simulations can substantially support stove design.

- CFD models can be applied to optimise
  - the combustion chamber design
    → gain sufficient residence time at high temperatures
  - the combustion chamber material selection and the radiation through the window
    → keep the combustion temperatures high
  - the positioning and dimensions of secondary air nozzles
    → improve mixing of the combustion air with the flue gases
  - the window purge air flow
    → keep the window clean and adjust the contribution of window purge air to primary and secondary combustion
  - the air staging concept
    → to generally improve the gas phase burnout
  - pressure losses

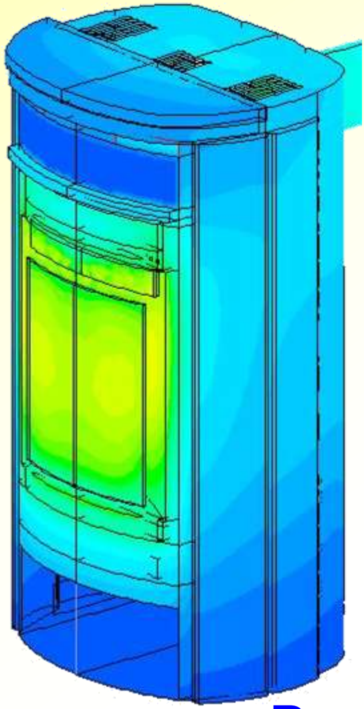
- Thereby, time for repeated prototype construction and testing can be saved and a targeted optimisation is possible

Summary and conclusions (I)

- **Guidelines for low emission chimney stove design have been presented**
- **The guidelines include recommendations regarding**
  - **general stove conception**
  - **stove dimensioning**
  - **strategies regarding material selection**
  - **implementation of air staging**
  - **implementation of an automated process control system**
- **Examples from practice have revealed that a basic version of a stove designed according to these recommendations already reaches acceptable emission levels.**
- **However, air staging and automated process control offer significant further emission reduction potentials**
  (see case study: CO by 60%, OGC by 86%, TSP by 55%)

Summary and conclusions (II)

- **The guidelines presented should only be considered as general recommendations.**
- **Modern and correctly designed stoves under consideration of the guidelines can show substantially reduced emissions and considerably increased efficiencies.**
- **A combination of primary measures and an automated stove control is seen as a suitable and also cost efficient approach in comparison to secondary measures (e.g. filters, catalysts).**
- **An automated control of a stove increases the user comfort and minimises user induced errors.**
- **In future appropriate labels and close-to-real-life testing methods should ensure that a better evaluation of stoves can be achieved and that quality differences are made clearly visible.**



Thank you for your attention

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