Particle Formation in Wood Combustion and New Concept for a Low-Particle-Furnace

M. Oser[1], Th. Nussbaumer[1], P. Müller[2], M. Mohr[3], R. Figi[3]
[1]Verenum, Zürich, [2]Müller AG, Balsthal, [3]EMPA, Dübendorf

Abstract

The aim of the present investigation is to analyse the aerosol formation mechanisms and to investigate the influences on particle emissions by variation of furnace design parameters and operating conditions. A laboratory plant based on a 80 kW under stoker furnace was designed which enables an independent variation of operation parameters. In contrast to the particles of Diesel engines most of the particles from the combustion of wood in automatic furnaces are salts (potassium and calcium compounds), while organic carbon contributes only with 1 to 2% to the particle mass.

Except for bark, the particles are mainly formed by the solid-vapour-particle path. The particle mass concentration is mainly influenced by the excess air in the glow bed. In the laboratory furnace the particle mass concentration could be influenced by a factor of 5 to 6 (from 160-195 mg/Nm^3 to 20-45 mg/Nm^3 (13 Vol.-% O_2). The particle number concentration is mainly influenced by the flue gas volume or the total excess air respectively. The reason of this connection is the influence on the coagulation. In the laboratory furnace the particle number concentration could be influenced by a factor of about 2.4 (from 19 to 8 $*10^7$/Ncm^3 (13 Vol.-% O_2). Based on these results a new concept for a low-particle-furnace is presented.

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The particles from wood combustion are quite different to the particles from Diesel engines. Previous investigations showed, that the organic portion of the particles from wood furnaces is small [Noger et al. 1996, Obernberger/Biedermann 1995]. In our measurements the organic portion always is below 5%. The main part are potassium compounds. In all of our measurements taken, more than 60% are potassium compounds, for example potassium sulfate and potassium chloride. Also calcium compounds like calcium carbonate and calcium oxide are important. Normally, the amount of them is smaller than 20%. The particles from wood combustion are mainly salts. The positive ions are potassium and calcium and others. The negative ions are sulfate, chloride, carbonate, oxide, hydroxide and others.

Typical number size distributions measured by SMPS are presented on figure 2 (left). The size distributions are similar to the distributions of Diesel engines. The mass size distribution has a main peak under 1 µm and sometimes a second peak by about 10 µm (figure 2, right bottom). The REM-picture on figure 2 shows typical particles of wood combustion [Kaufmann/Nussbaumer 1998].

The goal of the present research [Oser et al. 2003] is to analyse the particle formation of wood furnaces, to evaluate the reduction potential of the particle emissions by primary measures and to develop a concept of a low-particle-furnace with primary measures.

Theory and Hypotheses

From this research two hypotheses are delevoped from theoretical considerations: One of them concerns the particle mass concentration and the other the particle number concentration.

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As a consequence, hypothesis 1 is formulated:

Hypothesis 1: The particle mass concentration is mainly influenced by the excess air ratio in the glow bed.

Hence it's expected that the lowest particle mass concentration in the flue gas is reached by a low excess air ratio in the glow bed. However, the excess air ratio in the glow bed has to be high enough for a sufficient combustion temperature.

This graph on figure 4 illustrates the dependence of the total excess air ratio to the O_2-referred number concentration in the flue gas. The coagulation is considered with the formula of Fuchs [Fuchs 1964]. These connections leads to the formula on figure 4 below. This formula shows, that the number concentration is a function of the volume flow, which leads to our second hypothesis:

Hypothesis 2: The particle number concentration is mainly influenced by the volume flow of the flue gas or the total excess air ratio, respectively.

Methods

We performed our experimental exploration with an under stoker furnace with air staging (figure 5) designed for automatic combustion of wood chips. To be able to analyse the influence of the air staging, the 80 kW under stoker furnace in our laboratory (figure 6 left) was remodelled to such a degree that it can be operated in three stages: With primary (PA), seconday (SA) and tertiary air (TA). The secondary air can be added either earlier (SAe) or later (SAl) in the process (figure 6 right).

Results and Discussion

The experimentell results with beech wood chips and a distinct air staging using primary and tertiary air confirm hypothesis 1. The particle mass concentration in the flue gas decrease with decreasing excess air ratio in the glow bed from 160-195 mg/Nm^3 (13 Vol.-% O_2) by an excess air ratio in the glow bed over 0.7 to 20-45 mg/Nm^3 (13 Vol.-% O_2) by an excess air ratio of about 0.3 (figure 7: std: beech TA). Therefore, the particle concentration can be distinctively influenced with the excess air ratio in the glow bed.

Adding secondary air early instead of tertiary air, no further reduction of particle concentration is shown (figure 7: SAe). The explanation for this is the following: Reducing the primary air a great deal, the secondary air partially is able to flow back to the glow bed and thus locally increases the excess air ratio (figure 7 right). Reducing the tertiary air and thereby the total excess air ratio, no significant influence on the particle concentration was measured (figure 7: TA low). This proves, that the particle concentration is dependent on the excess air ratio of the glow bed and not on the total excess air ratio.

The experimentell results also confirm hypothesis 2: An almost linear correlation between the normalized volume flow and the number concentration was found independent of the kind of air staging. (figure 8)

Figure 9 shows the elemental composition of the flue gas particles of wet beech while comparing with wet bark of beech. The difference between the both of them (figure 9, column 3) makes clear, that bark is generating an addition of calcium and besides that some sulfur and oxygen, shown under others. The additional positive ions are Ca^{2+} and the additional negative ions are mostly SO_4^{2-}.

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Conclusions

Based on all existing scientific findings, the different paths of particle formation of wood combustion are presented on figure 11. The two paths, signed with number 1 and 2 are the most important by combustion of wood in automatic wood furnaces. The most important path number 1 is the solid-vapour-particle path with nucleation and coagulation. Most of the potassium compounds are formed on this path. The diameters of the particles formed on the solid-vapour-particle path are about 0.1 µm. The path number 2, called solid-to-particle path, generate particles with diameters of about 1 to 10 µm. Typically, CaO-particles are formed on this solid-to-particle path, since the volatility of CaO is very low. (figure 11)

The following two theoretical derived hypothesis are experimental verified:

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Based on our results, a concept for a low-particle-furnace with primary measures is developped. This low-particle-furnace has a low excess air ratio in the glow bed between 0.2 and 0.4 (for a low particle mass concentration), a low total excess air ratio between 1.3 and 1.4 (for a low number concentration) and a suitable geometry (e.g. high combustion chamber, distinct air staging). Further, a new automatic control system is needed. This automatic control system has to ensure the low-particle combustion by varying fuel and varying heating output. **This concept for a low-particle-furnace has a reduction potential of 75% for the particle mass and of 35% for the particle number.**

Acknowledgement

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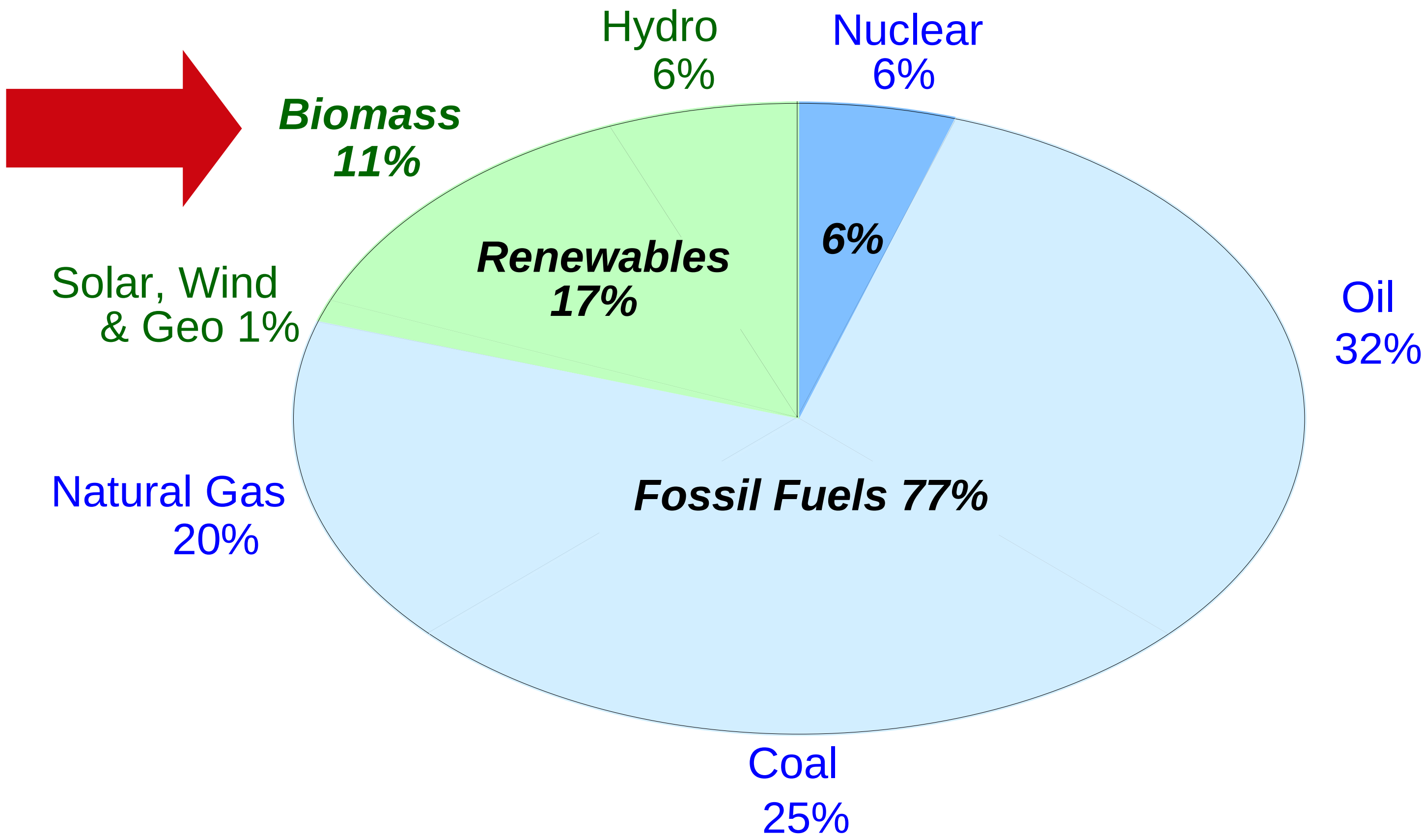
Introduction

Relevance of Wood Energy

Particles from Wood Combustion

Global Energy Consumption



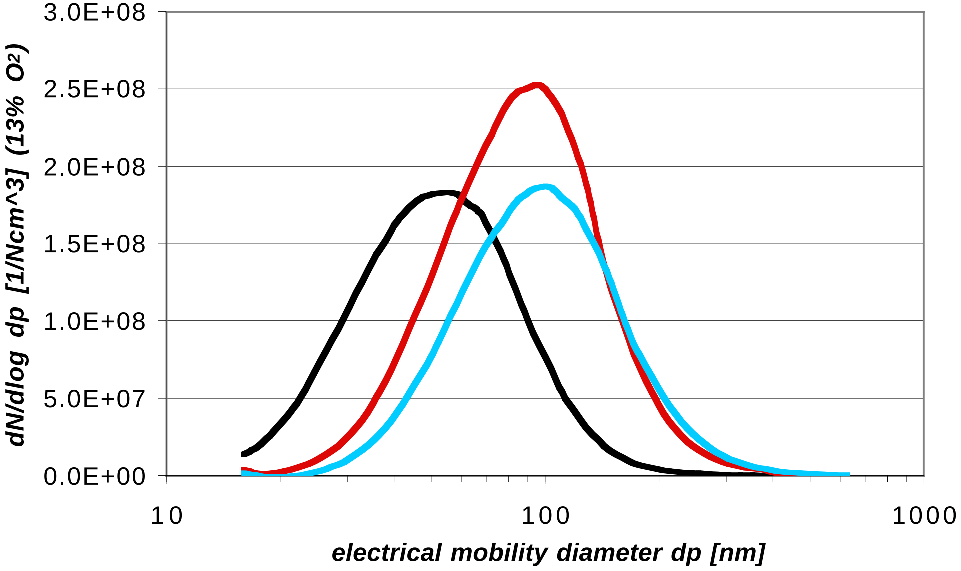
Global Energy Consumption
[World Energy Council 1995]

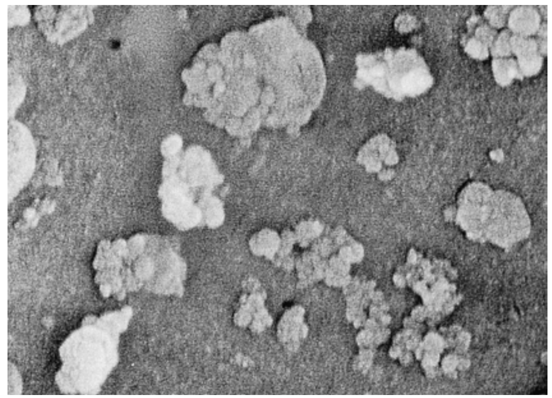
Chemical Composition

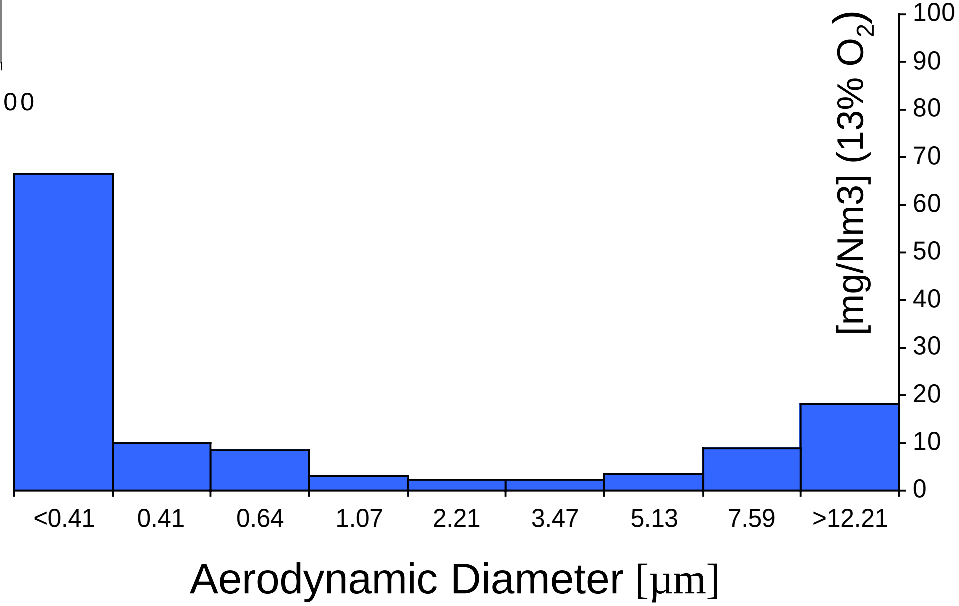
- Organic compounds <5% (Corg < 4%)
- ***Potassium compounds*** ***>60%*** (K about 30%)
  - K_2SO_4, KCl
- Calcium compounds <20% (Ca ≤ 8%)
  - $CaCO_3$, CaO

➔ mainly ***salts***:
Positive Ions: ***K^+, Ca^{2+},*** $CaMg^{2+}$
Negative Ions: SO_4^{2-}, Cl^-, CO_3^{2-}, O^{2-}, OH^-, $S_2O_7^{2-}$

Size Distribution







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Goal

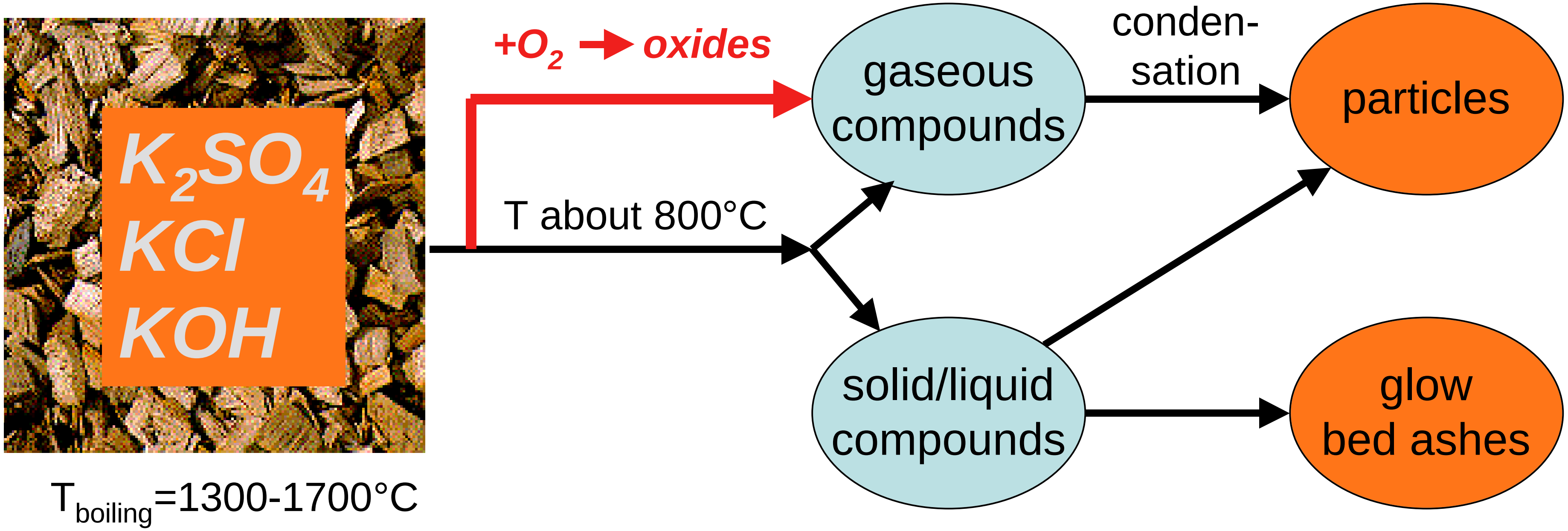
- particle formation of wood furnaces
- reduction potential of the particle emissions by primary measures
- concept of a low-particle-furnace

Theory and Hypotheses

Particle Mass Concentration

Particle Number Concentration

Source of Potassium (K)



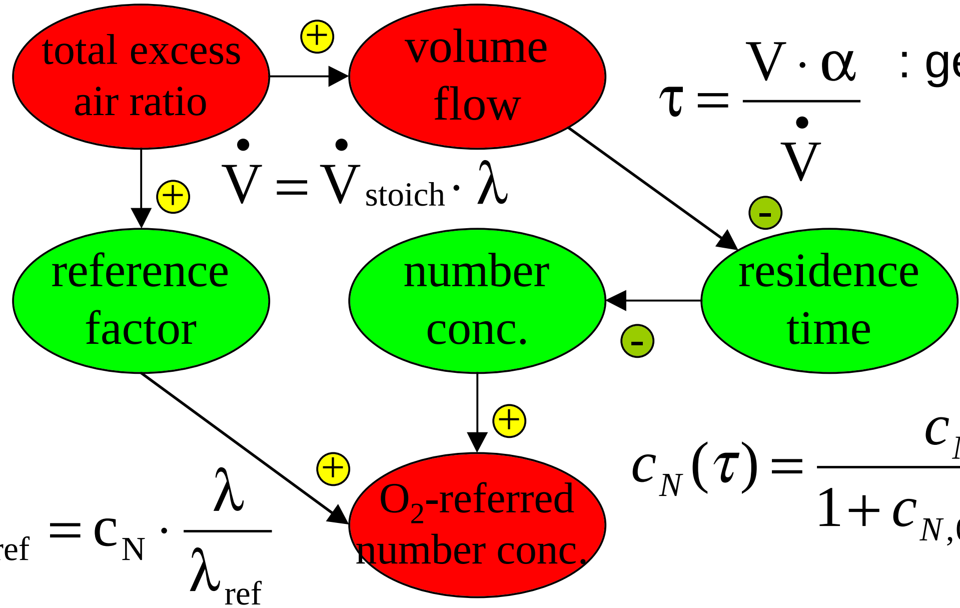
➔ Oxygen reduction in the glow bed should cause a smaller potassium load of the flue gas (lower particle mass)

Figure 3

Hypothesis 1

- ***The particle mass concentration is mainly influenced by the excess air ratio in the glow bed.***

Influences on the Number Concentration



$$\tau = \frac{V \cdot \alpha}{\dot{V}}$$: geometry factor

$$\dot{V} = \dot{V}_{stoich} \cdot \lambda$$

$$c_{N,ref} = c_N \cdot \frac{\lambda}{\lambda_{ref}}$$

$$c_N(\tau) = \frac{c_{N,0}}{1 + c_{N,0} \cdot K \cdot \tau}$$:coagulation [Fuchs]

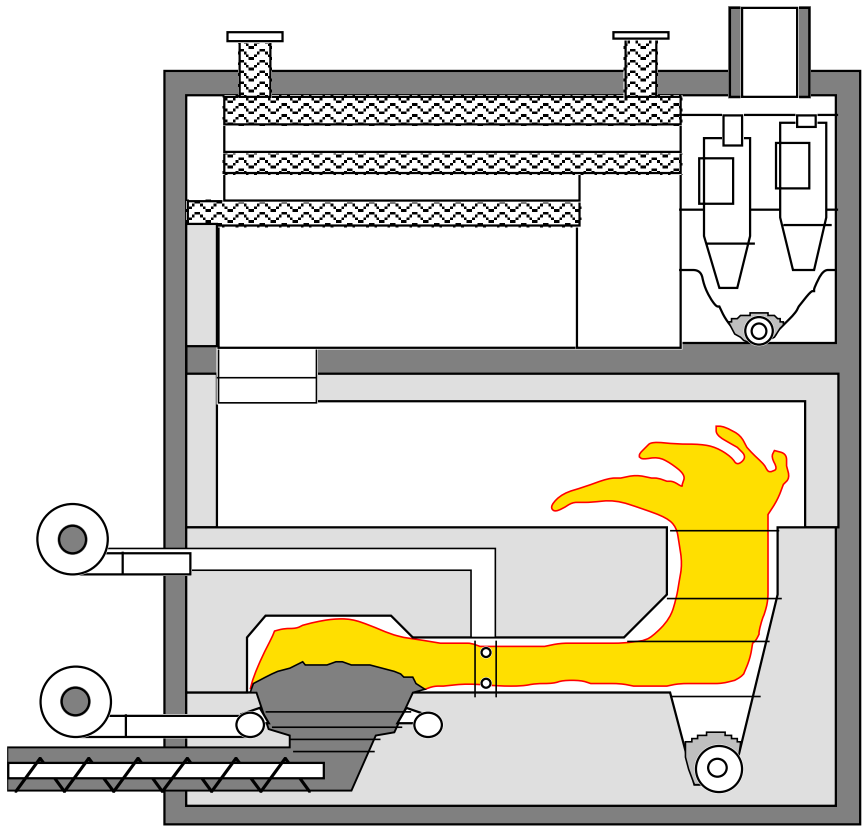
$$c_{N,Norm}(\dot{V}_N) = \frac{\dot{V}_N \cdot c_{N,0}}{\dot{V}_{NStoich} \cdot \lambda_{ref} \cdot \left(1 + c_{N,0} \cdot K \cdot \alpha \cdot V \cdot \beta_N / \dot{V}_N\right)} = \frac{x \cdot \dot{V}_N^{\,2}}{(\dot{V}_N + y)} \qquad \beta_N = \frac{\dot{V}_N}{\dot{V}}$$

Hypothesis 2

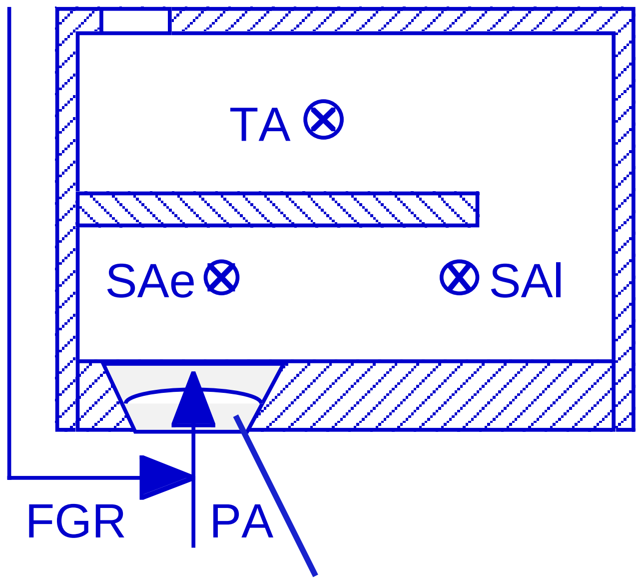
- ***The particle number concentration is mainly influenced by the volume flow of the flue gas or the total excess air ratio, respectively.***

Methods

Under Stoker Furnace



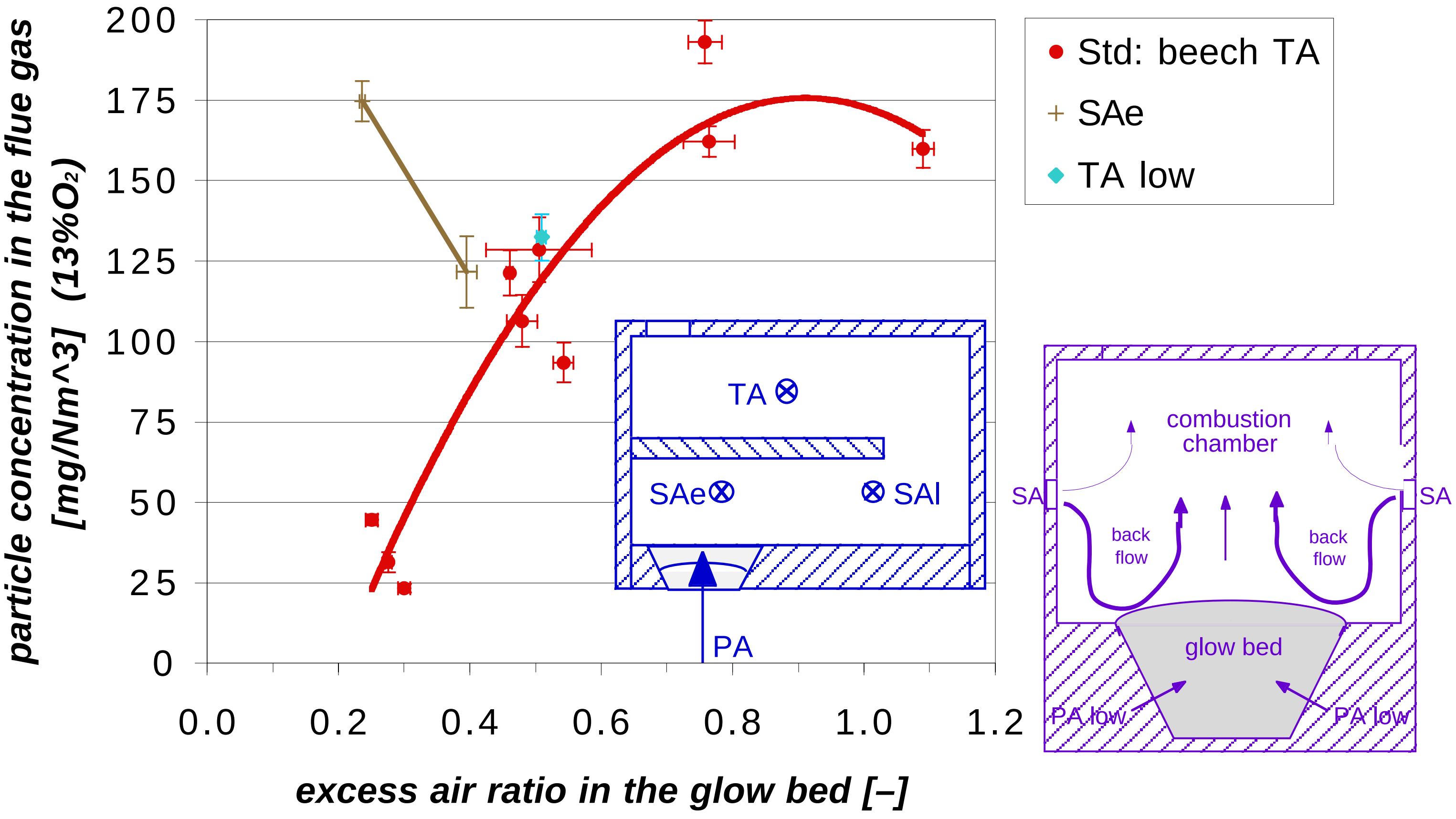
Test equipment



Excess air ratio in glow bed

Results and Discussion

Particle Concentration as a Function of Excess Air Ratio in the Glow Bed



Influence of the Volume Flow on the Number Concentration

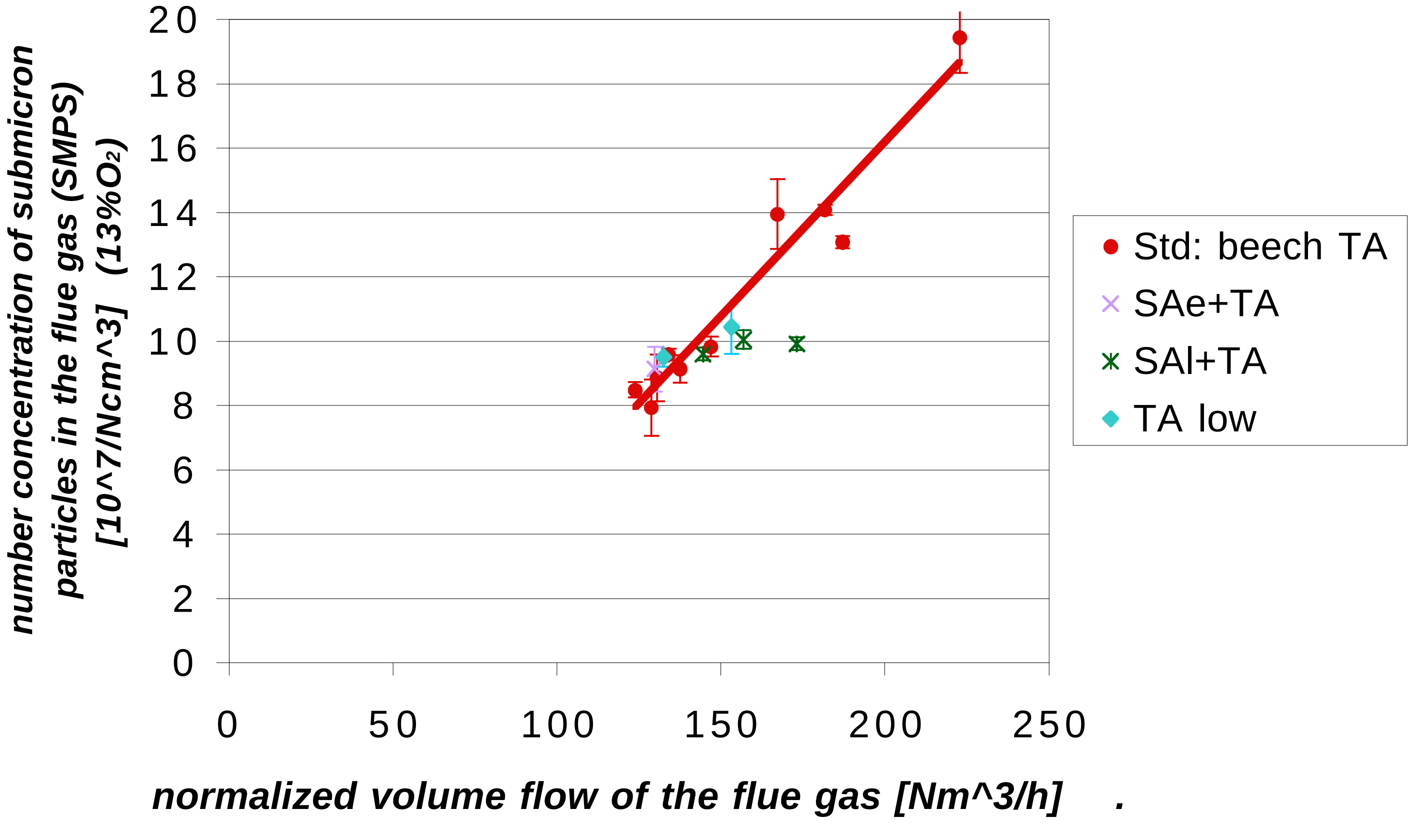
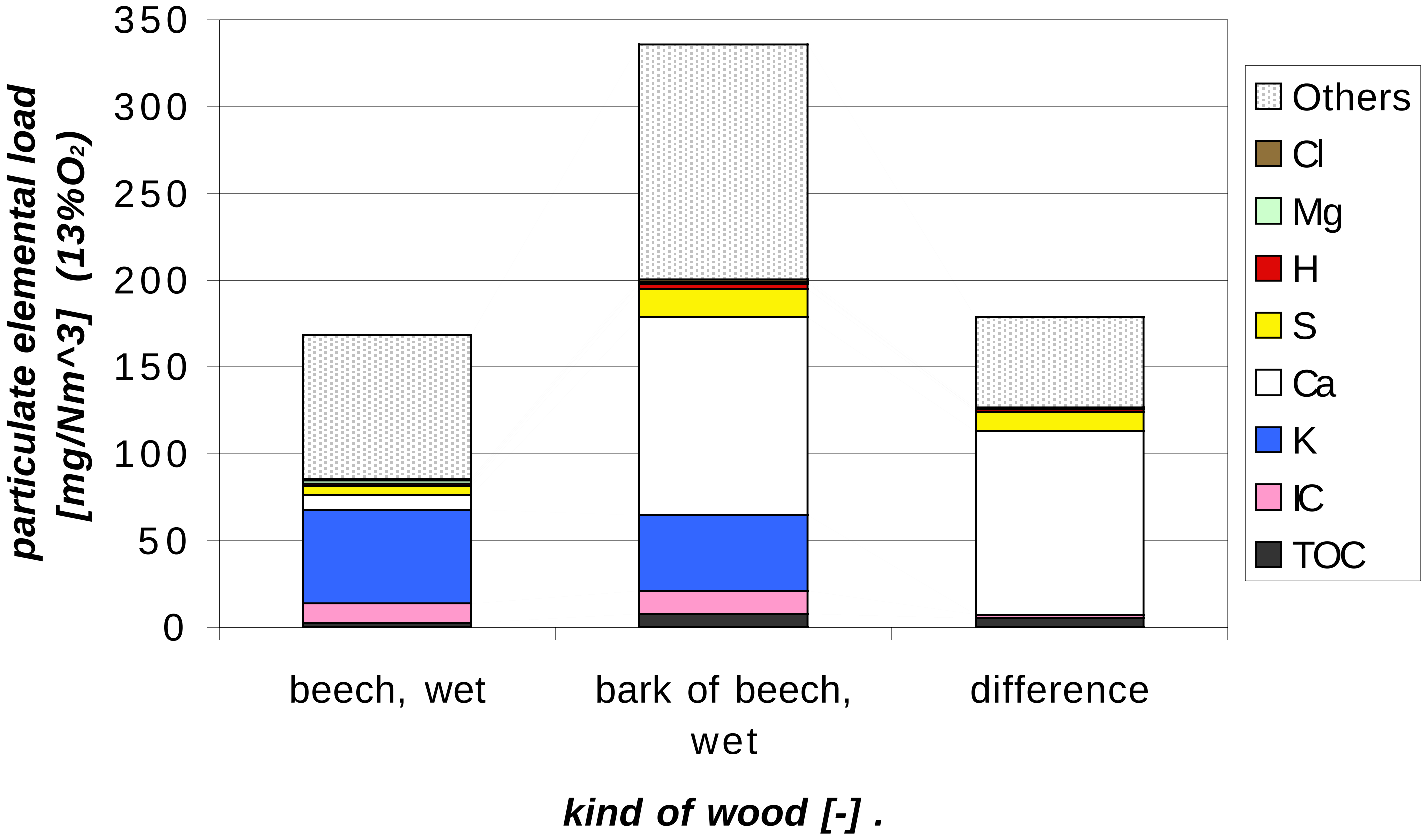


Figure 8

Influence of Bark to the Particulate Elemental Load



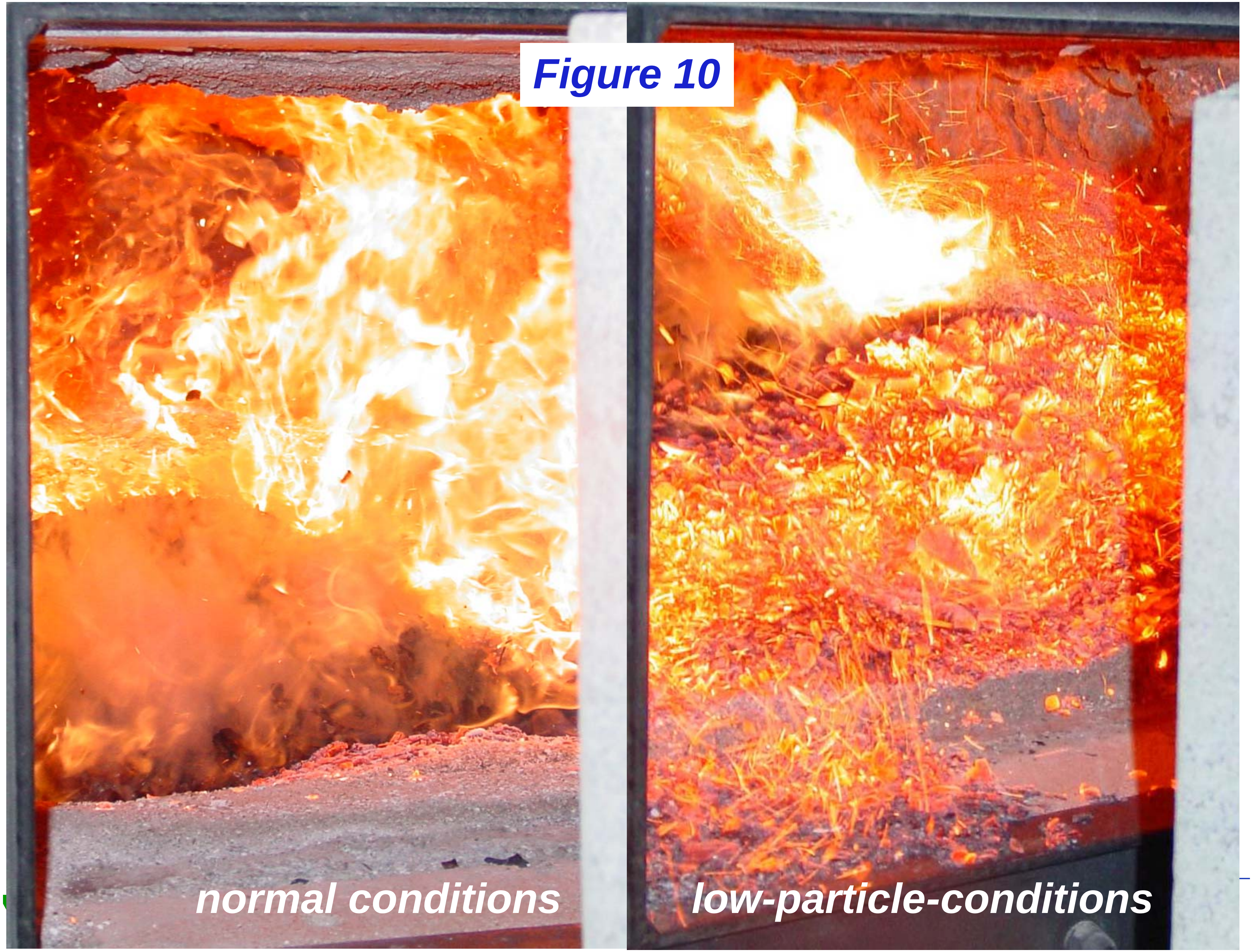


Figure 10
normal conditions
low-particle-conditions

Conclusions

Particle Formation

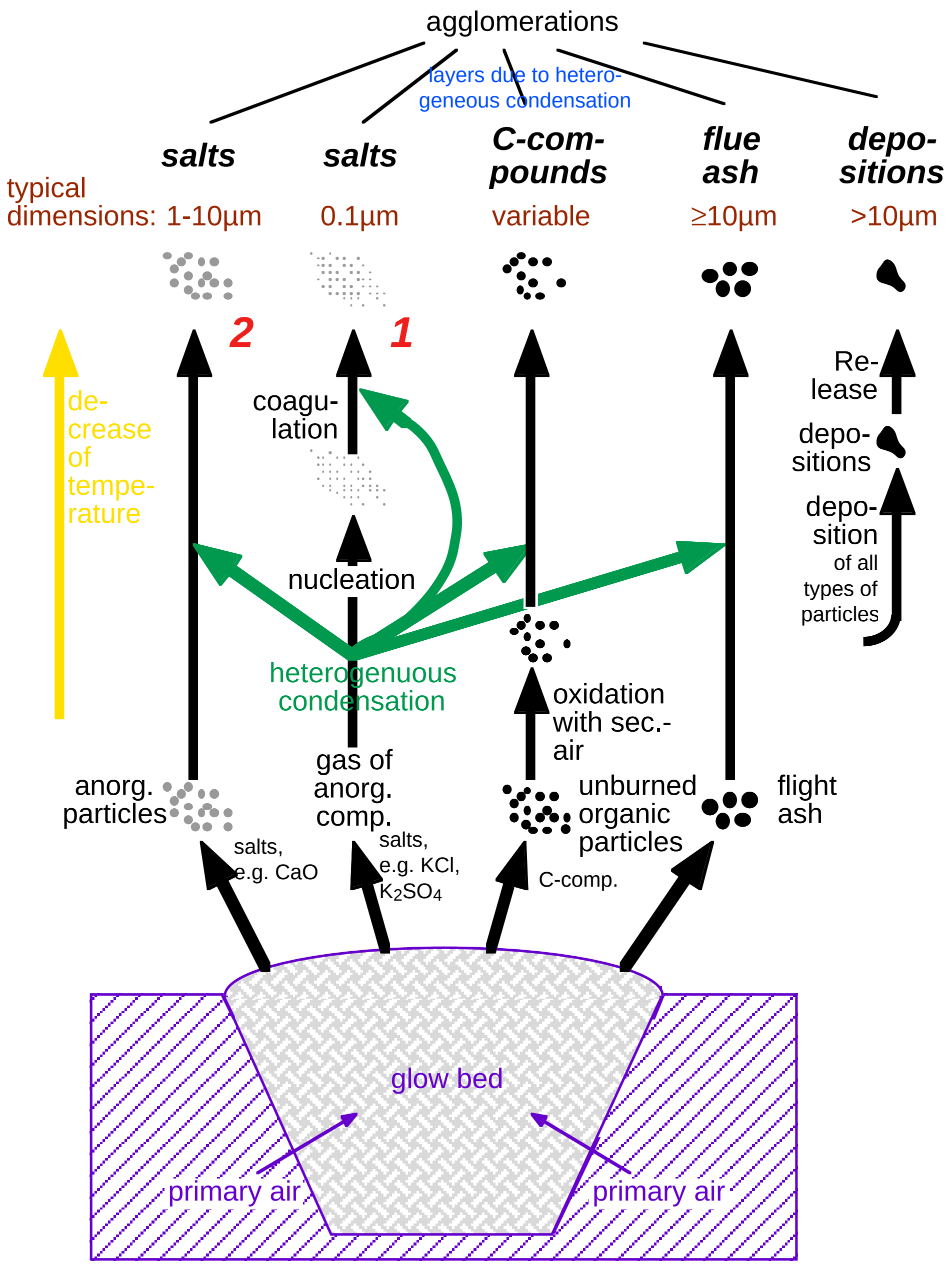


Figure 11

Conclusions

- ***2 hypotheses verified***
  - 1. particle mass concentration is mainly influenced by the excess air ratio in the glow bed
  - 2. particle number concentration is mainly influenced by the volume flow of the flue gas
- ***concept for a low-particle-furnace***
  - low excess air ratio in the glow bed between 0.2 and 0.4
  - low total excess air ratio between 1.3 and 1.4
  - suitable geometry
  - new automatic control system
  - ***75% reduction of particle mass (<50 mg/Nm^3)***
  - ***35% reduction of particle number***

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