



Influence of firebed temperature on inorganic particle emissions in a residential wood pellet boiler



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HIGHLIGHTS

- Water-based firebed cooling to investigate the influence of firebed temperature.
- Firebed cooling influences emissions of particles <0.3 μm.
- Particles <0.3 μm mainly consist of KCl.
- Firebed cooling had no significant influence on PM₁ and boiler ash chemistry.

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ABSTRACT

The temperature-dependent release of inorganic elements is the first step of the main formation pathway of particle emissions in automatically fired biomass burners. To investigate this step, a residential pellet boiler with an underfeed-burner was equipped with a direct firebed cooling. This test setup enabled decreased firebed temperatures without affecting further parameters like air flow rates or oxygen content in the firebed. A reduction of particle emissions in PM₁-fraction at activated firebed cooling was found by impactor measurement and by optical particle counter. The affected particles were found in the size range <0.3 μm and have been composed mainly of potassium chloride (KCl). The chemical analysis of PM₁ and boiler ash showed no statistically significant differences due to the firebed cooling. Therefore, our results indicate that the direct firebed cooling influenced the release of potassium (K) without affecting other chemical reactions.

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1. Introduction

The increased usage of solid biomass in combustion processes, especially for residential heating purposes has been identified as one of the main sources of particulate matter (PM) emissions across Europe (Maenhaut et al., 2012; Kumar et al., 2013; Viana et al., 2013). Particle emissions can be classified into organic and inorganic compounds. The inorganic compounds originate from noncombustible ash which is partly transformed to particulate

matter at combustion conditions. Organic particles arise from soot or condensed organic gaseous compounds (e.g. hydrocarbons) and are usually linked to poor combustion conditions (Schmidl et al., 2011; Lamberg et al., 2011; Fernandes and Costa, 2013). A high share of inorganic particles (>90%) and predominantly particles < 1 μm aerodynamic diameter (=PM₁) are typical for fully automated firing systems like wood pellet or wood chip boilers (Johansson et al., 2004; Schmidl et al., 2011; Fernandes and Costa, 2013; Kortelainen et al., 2015). The dominating elements of inorganic particles are K, Na, S, Cl and Zn (van Lith et al., 2008; Fernandes and Costa, 2013; Lamberg et al., 2013). Especially potassium (K) is considered to be the key component of PM from woody biomass combustion and its temperature-dependent release to the gas phase is well described in many publications

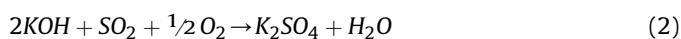
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(van Lith et al., 2008; Johansen et al., 2013; Fatehi et al., 2015). This process can be simplified in four steps as follows (Davidsson et al., 2002; Wiinikka et al., 2007; Sippula et al., 2008; Fernandes and Costa, 2013):

- I Evaporation in the firebed
- II Chemical reactions in the gas phase
- III Heterogeneous or homogeneous condensation during cooling
- IV Agglomeration of particles

The relevant chemical gas phase reactions of potassium (K) to particulate matter are simplified by the equations below. Potassium hydroxide (KOH) is assumed to be the released potassium compound from the fuel to the gas-phase (Glarborg and Marshall, 2005; Sippula et al., 2008; Hindiyarti et al., 2008; Li et al., 2013).



The temperature-dependent release of particle forming elements leads to several concepts of a reduced firebed temperature aiming at a reduction of PM-emissions. These methods can be summarized by the following approaches: a) exhaust gas recirculation, b) staged combustion and c) low primary excess air (Yin et al., 2008; Houshfar et al., 2012; Nunes et al., 2014; Kortelainen et al., 2015). While exhaust gas recirculation is mainly used in medium to large scale biomass combustion, staged combustion in combination with low primary excess air is state-of-the-art in small-scale biomass combustion. All of these measures are common to influence the firebed temperature by means of a reduced oxygen content and therefore a slowed down combustion process with decreased temperatures in the firebed. Since the air mass flow (e.g. low primary air) or the oxygen content (e.g. exhaust gas recirculation) are affected by these measures it is difficult to clearly differentiate related effects from those affected by lowered firebed temperatures. Furthermore, PM reduction by decreased firebed temperatures works only in combustion systems with a good burnout and low organic emissions.

The possible impact of the oxygen content inside the firebed on the release of particle precursors is described by Nussbaumer (2003) and Carroll et al. (2015). Nussbaumer (2003) states lower melting points of oxidized potassium salts in the firebed at high primary air as the relevant mechanism and describes a connection between primary air and particle emissions.

For a better understanding of these effects a firebed cooling similar to a water-cooled grate was developed to investigate the effect of firebed temperature on particle emissions without affecting air mass flow and/or oxygen content. Thus, the applied direct firebed cooling allowed for an exclusive analysis of decreased firebed temperatures in a residential biomass boiler with respect to the release of particulate matter. Important combustion parameters like excess air (λ), primary air, air mass flow rates and oxygen content in the firebed were kept at constant levels during the test runs at full load. A description of the test setup and a detailed study of the firebed cooling, temperature measurements, gaseous emissions and particle emissions (TSP = total suspended particles) can be found in a previous work (Gehrig et al., 2015). It was shown, that the firebed cooling can decrease the TSP statistically significant by about 17 wt%, accompanied by a statistically significant increase of gaseous HCl.

The objectives of this study included an investigation of the influence of firebed temperature (i) on particle emissions under real combustion conditions, (ii) on the chemical composition of

emitted particles as well as boiler ash and (iii) on the release of particle precursors, as well as on particle formation process in general.

2. Materials and methods

2.1. Test fuel

The used test fuel were wood pellets according EN 14961–2:2011 in A2-Quality (Table 1). A chemical analysis of the wood pellets can be found in Table 2.

2.2. Pellet boiler and firebed cooling

The used pellet boiler (KWB, Easyfire), a small-scale residential pellet furnace for hot water generation and central heating systems (classified according to EN 303–5:1999), had a thermal output of 12 kW using the combustion technology of an underfeed-burner with a staged combustion. The boiler was running ≥ 90 min at full load prior starting measurements to realize thermal equilibrium. The return flow was 59 ± 1 °C, cooled by a cooling unit and an interconnected heat storage ($V = 0.3 \text{ m}^3$) (Fig. 1). Details of the operating parameters are listed in Table 3. The applied measures allowed for constant and repeatable test conditions. The firebed cooling was realized by a water pipe welded underneath the burner plate. Details on the realization and function of the cooling and modifications made can be found in Gehrig et al. (2015). The experiments were done with firebed cooling (cooling ON) or without

Table 1
Physical fuel parameters (all specifications are mean values of $n = 3$ samples).

| Parameter/standard | |
|-----------------------------------|-------------------------|
| Diameter | |
| EN 16127:2012 | 6 mm |
| Bulk density | |
| EN 15103:2009 | 678 kg/m ³ |
| Moisture content | |
| EN 14774–2:2009 | 7.2 wt% |
| Calorific value ($q_{p,net,d}$) | |
| EN 14918:2009 | 18.90 MJ/kg |
| Ash melting behaviour | |
| DIN CEN/TS 15370–1:2006 | |
| SST/DT/HT/FT | 1005/1290/1380/>1470 °C |
| Ash content (at 550 °C) | |
| EN 14775:2009 | 0.52 wt% d.b. |

Table 2
Chemical analysis of fuel (all specifications are mean values with standard deviation of $n = 3$ samples, at dry fuel base).

| Element | | | Method |
|---------|----------|-------|--------------------------|
| C | 507 | g/kg | EN 15 104:2011 |
| H | 60 | g/kg | EN 15 104:2011 |
| N | 3.9 | g/kg | EN 15 104:2011 |
| O | 424 | g/kg | Calculated by difference |
| P | 264 ± 32 | mg/kg | EN ISO 11 885:2009 |
| S | 60 ± 5 | mg/kg | EN ISO 11 885:2009 |
| Cl | 132 ± 30 | mg/kg | EN ISO 15 682:2001 |
| Na | <7.5 | mg/kg | EN ISO 11 885:2009 |
| Mg | 118 ± 6 | mg/kg | EN ISO 11 885:2009 |
| K | 621 ± 16 | mg/kg | EN ISO 11 885:2009 |
| Ca | 889 ± 27 | mg/kg | EN ISO 11 885:2009 |
| Mn | 86 ± 3 | mg/kg | EN ISO 11 885:2009 |
| Fe | 55 ± 9 | mg/kg | EN ISO 11 885:2009 |
| Cu | <1.2 | mg/kg | EN ISO 11 885:2009 |
| Zn | <0.8 | mg/kg | EN ISO 11 885:2009 |
| Cd | <1.4 | mg/kg | EN ISO 11 885:2009 |
| Pb | <0.06 | mg/kg | EN ISO 11 885:2009 |

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