



Physical properties of aerosol particles measured from a bubbling fluidized bed boiler



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HIGHLIGHTS

- The combustion process was studied by sampling the aerosol particles from the boiler.
- In the boiler, the particle size distribution was unimodal in the measurement range.
- Gas phase species formed a second smaller particle mode in the dilution.
- The larger mode particles were more dense.
- Ferric sulfate additive decreased the number and mass of the smaller mode particles.

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ABSTRACT

Increased use of biomass and waste fuels, and the consequent corrosion problem have led to an increased need to study and monitor the combustion processes. This study presents an extensive physical characterization of aerosol particles measured from a bubbling fluidized bed boiler with different fuel mixtures and optional ferric sulfate feeding. The fuel mixtures included bark, sludge, peat and solid recovered fuel. Previously, the characterization of the particles analyzed from a fluidized bed reactor has mainly focused on chemical off-line analysis of collected impactor samples, large coarse mode particles or laboratory-scale reactors. In this study, the focus is in the particle size range from 3 to 500 nm, where mobility size distributions, effective density, morphology and electric net charge of particles were measured and analyzed. In the boiler, the particle size distribution in the measurement range was unimodal. Gas phase species formed a second smaller particle mode in the dilution. The number concentration of the smaller mode, peaking around 20 nm, was mostly dominating but variations were seen with respect to measurement location, fuel mixture and additive feeding. The effective density of these particles was approximately 1.4 g/cm³. The larger mode, peaking around 80 nm, was found to be more stable and the effective density of these particles decreased as a function of particle size, being 3–4 g/cm³ at the maximum. The results of this work suggest that the cores of these particles already exist in the boiler and partly consist of heavier lead and zinc compounds. The ferric sulfate feeding decreased the number and mass concentration of the smaller mode particles, which are formed in the sampling and dilution processes mainly from the gas phase alkali chlorides. These condensable species were also linked to the negative net charge of particles. This study deepens the understanding of the combustion process and the sampling of aerosol particles with an aspect of on-line monitoring.

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1. Introduction

The utilization of biomass and waste in energy production has significantly increased in recent years. The main reasons for this

development are global warming concerns and the need to reduce fossil fuel burning. In addition, new manners are being sought to treat different waste products cost-effectively and to avoid dumping them at landfill sites. Unfortunately, burning of biomass and waste incineration lead to various ash related problems in power plants [5,28,4,9,13]. So far, the most well-known problem is the

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high temperature corrosion of the superheaters in a boiler, induced by alkali chloride deposition [30]. Also other elements found in fuels, such as bromine, have been indicated to have similar effects [34]. Altogether, the increased utilization of biomass fuels and different waste fuels has led to an increased need to study the combustion process and to develop fuel additives against corrosion.

The corrosion problem is based on the fact that most biomass fuels and waste fuels have a relatively high content of alkali metals and chlorine, but they contain clearly less sulfur than fossil fuels. In a boiler, alkali chlorides are found to be in the gas phase. They tend to condense on the boiler heat transfer surfaces and form complex alkali salts with iron and other elements in the heat transfer components. These salts are highly corrosive. However, it has been showed that, by spraying sulfate containing compound into the flue gas after the combustion is completed, the corrosion can effectively be reduced [11]. Consequently, before the flue gas reaches the superheater, alkali chlorides are effectively converted to alkali sulfates. These compounds are more stable and much less corrosive than alkali chlorides. Several reagents have been protected for the application with patents [3]. These compounds are $(\text{NH}_4)_2\text{SO}_4$, NH_4HSO_4 , H_2SO_4 and FeSO_4 . Also co-combustion with peat has been shown to reduce corrosion [18].

To study the effects of fuel additives and fuel components on corrosion, the instrumentation of the in situ measurements of gaseous alkali chlorides has been developed. Several methods capable of on-line analysis of metal species in industrial processes are extensively reviewed by Monkhouse [29]. A few applications have recently been developed to define the amount of KCl and NaCl in the hot flue gas channel, i.e. the in situ alkali chloride monitor, IACM, based on the differential optical absorption spectroscopy [8] and the CPFAAS (collinear photofragmentation and atomic absorption spectroscopy) method presented by Sorvajärvi et al. [33]. The advantages of these methods are that no gas preparation system is needed and measurements are performed in situ. However, the calibration of the instruments is not trivial and it should be performed in similar temperature conditions as the measurement. These sort of optical instruments are also fairly expensive.

In addition to the reagents mentioned earlier, Aho et al. [2] showed that also aluminium sulfate and ferric sulfate, i.e. $\text{Al}_2(\text{SO}_4)_3$ and $\text{Fe}_2(\text{SO}_4)_3$ respectively, have similar tendency to prevent corrosion. In studying these alternative reagents, aerosol particle and fly ash measurements have had an important role. A specific sampling system enables the measurement of aerosol particles from the flue gas. After an air-cooled sampling probe and a two-step dilution, particles can be collected with a low pressure cascade impactor or led through an additional dilution to other aerosol measuring devices. Most of the studies based on this sampling system rely on the chemical off-line analysis of the collected impactor samples [2,34,35]. An electrical low pressure impactor, ELPI [19], has been used in these measurements to provide an aspect of on-line monitoring, but the instrument data has not been analyzed further.

In general, the physical properties of aerosol particles measured from flue gas and the formation processes of these aerosols have been widely studied since 1990s. In straw-fired boilers, the variety of experimental methods have been extensive, including low pressure impactors (LPI), scanning mobility particle sizers (SMPS) and electron microscopy [6,7,40]. The focus has been in sub-micron particles and understanding the formation of the particles [12]. In fluidized bed reactors burning waste and biomass, the research has focused on low pressure impactor measurements and electron microscopy of particles larger than one micron [23,36,13]. More recently, Lind et al. [24] and Sippula et al. [32] have been investigated the composition and the formation mechanisms of the aerosol particles measured from a laboratory scale fluidized bed reactor.

The main purpose of this study is to broaden the analysis of aerosol particles measured with the previously presented sampling system [2]. So far, the chemical composition of the flue gas particles measured from a full scale fluidized bed reactor has been studied in many different cases, but the physical properties, especially in the size range below 500 nm, have not been characterized at all. In this study, aerosol size distributions, the physical structure and the electric net charge of the particles are considered. The analysis is based on the measurements at a bubbling fluidized bed (BFB) boiler. An important aspect is how the ferric sulfate feeding affects the properties of aerosol particles. The final goal in that sense is the on-line monitoring of additive feeding processes. In addition to this possibility, this study aims at more profound understanding of the combustion process and the sampling of aerosol particles. To support the physical characterization and to connect the results to previous studies, also chemical off-line analysis of collected impactor samples is presented.

2. Experimental

2.1. BFB boiler and measurement locations

The experiments were carried out at the co-incineration plant of Anjala Paper Mill located in southern Finland during a two-week campaign. Detailed information on the plant and its history is given by Vainikka et al. [34]. Briefly, the plant started as a pulverized coal boiler but was converted to BFB boiler in 1995. The change enabled the utilization of solid recovered fuel (SRF) as a fuel component, and after 2006, the SRF share from all fuels was increased to 60%. The flue gas cleaning system includes an electrostatic precipitator (ESP) and a wet scrubber, from which the latter was installed in 1995. The ESP is designed to remove particulate emissions and the wet scrubber gaseous components. With this system, the plant could meet the EU Waste Incineration Directive (WID) emission limits [34].

The schematic of the BFB boiler is presented in Fig. 1. The furnace size is approximately $8 \times 8 \times 30$ m. Fuel is introduced to the furnace at the height of 3.5 m from the grate. The secondary air feeding takes place at 5.5 m and tertiary air feeding at 15 m from the grate. After the tertiary air addition, the air to fuel ratio is approximately 1.37. The flue gas temperature is at its highest 950 °C downstream from the secondary air feeding. In between the superheater tube blanks it is 740 °C and in the second pass under 400 °C. The economizers and air pre-heaters are located in the second pass.

In this study, the flue gas sample was taken either from the superheater area or from the second pass of the boiler. The temperatures at these locations in the boiler are 740 °C and 400 °C, respectively. The measurement locations were chosen in order to study the flue gas composition in the superheater and reveal the possible changes of the composition while moving downstream to the second pass. These objectives are directly connected to the corrosion problem caused by the wall deposition of different compounds.

2.2. Fuels, fuel mixtures and fuel additives

The boiler is designed to handle firing fuel mixtures of SRF, Scandinavian spruce bark, and dried paper mill sludge. The SRF originates from southern Finland and has undergone homogenization to 50–100 mm particle size and magnetic separation. In addition, PVC based packaging plastics have been excluded during the collection and preparation. SRF is delivered to the facility in wrapped bales or fluffs. The bark comes from the debarking processes of the adjacent paper mill while the sludge comes from the waste water treatment facility of the same mill [34]. The fuel mixtures

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