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Particle sampling in boilers of waste incineration plants for characterizing corrosion relevant species

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ABSTRACT

A novel probe has been developed to characterize particles in boilers of waste incineration plants, which are under suspicion to essentially drive the corrosion processes. The probe collects larger particles on impaction plates and smaller particles on membranes, whose deposition characteristics have been studied by computational fluid dynamics. Artifacts by condensation of salt vapors are largely suppressed. The size distribution, morphology and chemical properties of the particles can be investigated by scanning electron microscopy and energy-dispersive X-ray spectroscopy. The probe has been employed for measurements in a waste incineration plant to characterize the aerosol on its way through the boiler.

1. Introduction

The corrosion in boilers of municipal solid waste incinerators (MSWI) gives rise to a high loss in resources [1–3], which concerns the consumption of metallic materials as well as constraints in reaching an optimum efficiency and availability. Primarily affected by corrosion are the first superheater packages at raw gas temperatures of about 550 °C. It is known that the high-temperature chlorine corrosion is the main driving mechanism [4–8]. However, the corrosion rates strongly vary between different plants of similar construction and waste mixture, which is not yet completely understood. Since the exclusive presence of chlorine containing gases such as HCl cannot explain the severe corrosion observed [9,10], there is the reasonable suspicion that chlorine containing particles play a major role in the corrosion processes. Therefore, a correlation between the corrosion rate and the properties of the particulate phase such as its concentration, size distribution, morphology and chemical composition is expected.

Whereas there are many studies on the reacted particle deposits on the superheater tubes [11–16], the airborne particle phase in the boilers of MSWI is only rarely investigated: Brunner et al. used a high temperature cascade impactor to collect size fractioned particles from the boiler [17]. However, the method is limited to particles smaller than about 1 μm since the aerosol is extracted normal to the main flow direction which limits the aspiration efficiency for larger particles due to their inertia. Deuerling et al. exhausted the raw gas isokinetically and quenched it with a porous tube diluter (PTD) to make it available for conventional aerosol measurement techniques [18,19]. However, at high temperatures this method introduces tremendous artifacts by condensation of alkali chloride vapors during the cool-down in the PTD [20]. Since the saturation vapor pressure of NaCl and KCl drops by a factor of more than 10^6 when cooling from 1000 to 500 °C [21], a dilution factor on the same order is needed to suppress artificial condensation. This is technically hardly achievable and would make the particle concentration immeasurably small. A further disadvantage of the PTD method is a lack of information on sticky particles with sizes from about 1 to 25 μm since they deposit in the goose-neck inlet of the probe and therefore cannot be size fractionated [19].

In this work, we developed a new concept to collect the particles directly in the hot zones of a MSWI boiler on sample substrates for subsequent analysis. The method allows morphological and chemical characterization of single particles over a broad size range. The airborne particle size distribution is reconstructed after sizing and

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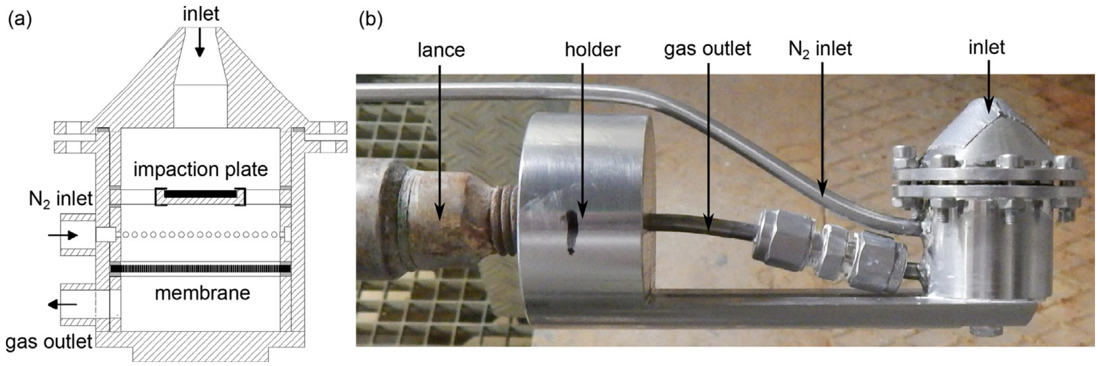

Fig. 1. (a) Cross section of the probe showing the two stages of particle sampling. (b) Photograph of the probe mounted on the holder which is screwed on a lance.

counting the collected particles. Several means are applied to minimize artifacts by salt vapor condensation. In the following section, we will present the design of the probe and its collection characteristics. First results from measurements in an industrial MSWI are shown in Section 3 and discussed afterwards.

2. Probe design

A cross section of the newly developed probe is shown in Fig. 1(a). The body is manufactured from the heat- and corrosion-resistant steel 1.4841 in order to withstand the high temperature and corrosive atmosphere in an MSWI boiler (see also Supplemental material). The cap is connected to the housing by a flange which allows easy access to the inside. For entering the boiler, the probe is mounted on a stainless steel holder screwed onto the tip of a water-cooled lance as shown in Fig. 1(b). The total height of the probe is limited to approximately 45 mm, which allows insertion even through small 50 mm ports in the boiler walls. By rotating the lance, the orientation of the probe inlet can easily be adapted to the flow direction of the flue gas (either up- or downwards depending on the pass). Isokinetic sampling at the given flue gas velocity of 4.5 m/s is achieved by a circular inlet nozzle of 3.1 mm diameter and an operating flow rate of 2 l/min provided by a rotary vane pump exhausting at the gas outlet.

To avoid artifacts by condensation and chemical reactions, the probe is flushed with an excess of pure nitrogen before and after sampling: Initially, the probe is inserted into the boiler and preheated to the temperature of the surrounding gas, while the nitrogen excess flux prevents particles and gas from entering. Supportively, the inlet of the probe is rotated by 90° with respect to the flue gas direction. By swiveling in the probe and switching off the nitrogen flux the sampling is started with high temporal precision. When switching the nitrogen flux back on and swiveling out the probe the sampling is completed. The probe is extracted from the boiler and the sampling substrates cool down in the inert nitrogen atmosphere.

The interior of the probe contains two different sampling stages to cover a broad particle size spectrum: Larger particles entering the probe are sampled on an impaction plate due to their inertia. This avoids fast clogging of the following filter substrate, which is used for collecting the remaining smaller particles. The design, choice and collection characteristics of both stages will be discussed in the following.

The impactor has been designed such that it reaches a cut-off diameter of more than 10 μm while sampling isokinetically at the given flue gas velocity of 4.5 m/s. This combination requires a geometry beyond the applicability of the classical impaction theory [22]. Therefore, we performed computational fluid dynamics (CFD) simulations using ANSYS FLUENT and the integrated discrete phase model (DPM) to design an impactor with the desired separation characteristics. The calculations have been conducted two-dimensionally with rotational symmetry around the central axis. The corresponding geometry is shown in Fig. 2(a): N_{inj} spherical particles with varying diameters are distributed equilaterally over the inlet with a horizontal velocity of 4.5 m/s. The particle density is set to 2200 kg/m^3, which has been shown before to be a typical average density for fly ash particles in MSWI [19]. The temperature is taken into account by the density and viscosity of the carrier gas. After partial deposition on the impaction plate, the number N_{esc} of particles reaching the outlet is determined. From that, the collection efficiency is calculated to

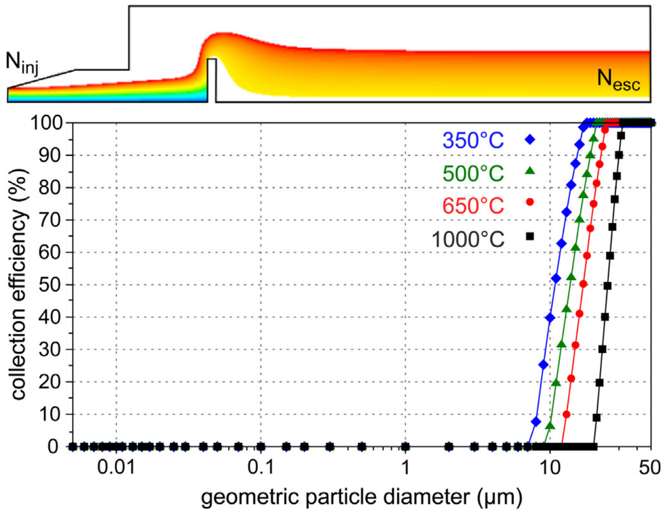

Fig. 2. Two-dimensional domain (rotational axis on the bottom) for CFD simulations on the impactor characteristics at different temperatures. Particle trajectories are drawn with a color gradient from blue (injection closest to the rotational axis) to red (injection furthest from the roational axis). The deposition efficiency is calculated from the fraction of particle trajectories reaching the outlet. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

$$\varepsilon = \left(1 - \frac{N_{esc}}{N_{inj}}\right)^2 \tag{1}$$

taking into account the three-dimensionality of the actual geometry. At all temperatures, the impactor reveals steep cutoff curves. The geometric cutoff diameter increases from 11 μm at 350 °C to 25 μm at 1000 °C (corresponding to aerodynamic diameters of 16 μm and 37 μm, respectively). The pronounced temperature dependence is only partially caused by the viscous drag on the particle, but the streaming inside the impactor which develops differently depending on the temperature has a larger effect. The