New emission sampling system for particle number concentration up to 10^9/ccm

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1 Abstract

The GRIMM emission sampling system in combination with a scanning mobility particle sizer allows continuous online measurements of particles in the size range 3nm to 155nm with a resolution of 44 size channels. Single channel measurements can be performed with a time resolution of up to 8 Hz. The system is portable, easy to install, robust, and only needs a power outlet for operation. It is therefore ideal for process control and emission measurements.

The precise particle sizing allows a conversion of the measured number distribution in dust mass concentration, online with a software package.

The system was tested on several applications, e.g. wood combustion, automotive emissions, emissions of printer and copy machines. Results of number and mass distribution and total particle number and mass concentration will be shown with respect to different emission sources and operation settings.

Due to the easy operation and fast response the system is suitable for online testing of emission sources, both and mitigation techniques like filters or precipitators.

2 Introduction

Aim of this study was the performance test of a emission sampling system for different combustion aerosol with very high concentrations.

The main experiment was the continuous on-line determination of the particle size distribution in the exhaust gas of a pellet burner and the calculation of the emitted dust mass during constant operation at 15kW. Ignition, warm-up phase and burn-out phase of the burner operation were not the main focus. Additional test have been done at a large diesel generator with and without filter elements and in the exhaust of a airplane turbine test rick

Motivation for this type of investigation is the recent revision of limit values for fine dust emissions from wood combustion in Germany, [1] BImSchV 2010. In particular the burners with an energy output <15kW, which have been added to the new guidelines. The fine dust limit values will be reduced in two steps while differentiated according to the burner type, the biofuel type and the nominal heat capacity.

For Pellet burner the new limit values are:

Limit value step 1: fine dust: 0,06g/m³, CO: 0,8g/m³, energy output >4 to 500 kW

Limit value step 2: fine dust: 0,02g/m³, CO: 0,4g/m³, energy output >4 kW

In order to conduct this study a special scientific pellet burner and a wood gas burner both with a nominal heat capacity of 15kW were used, available at the University of Applied Science in Ulm, Germany. The results presented in this paper are from the pellet burner only. The pellet burner is equipped with a automated feeder and uses standardised pellet material.

The filter efficiency tests at the diesel engine have been performed at the company Bredenoord in the Netherlands. The exhaust measurements of the airplane turbine test rick have been done at the gas turbine research centre, GTRC of Cardiff University.

2.1 Material and methods

Figure 1 and Figure 2 show both burners. The pellet burner is a non-commercial prototype for scientific use. It was designed for the evaluation of different scenarios and their effects on the dust and CO emissions. The burner is connected to a 6m³ boiler and equipped with various sensors for heat capacity, thermal capacity, electrical power consumption, volume flow, flow and return temperature and pellet consumption.

For the particle sampling a new emission sampling system (ESS) for hot gas was used, that allows the particle sampling without condensation. The exhaust gas is diluted in a fixed ratio 1:10 or 1:100 with pre heated, clean, particle free, dried air. The temperature of the sampling probe can be adjusted up to 400° and was set to 140° for this experiment. The status of the sampling probe is indicated online by means of LEDs.

The volume flow of the dilution air is controlled by a heated critical orifice and an integrated pump and kept constant at 9 l/min. The dilution air is fed back in a reverse flow with an integrated absolute filter and active carbon filter, a silica gel dryer and a second absolute filter. The cooling of the diluted sample air is done by a heat sink at the end of the sampling probe.

Figure 1: Pellet burner (blue) and wood gas burner (red) in the laboratory of Dezentrale Energiesysteme at the institute for energy technique and motion technique, University of Applied Science, Ulm.

Figure 2: Pellet burner with pellet storage and auto feeding system. Legend: 1: Storage for wood pellets, 2: Electrical auto feeding system, 3: Pellet burner with control unit and housing, 4: Burner, adapted for experimental use, originally a simple wood burner.

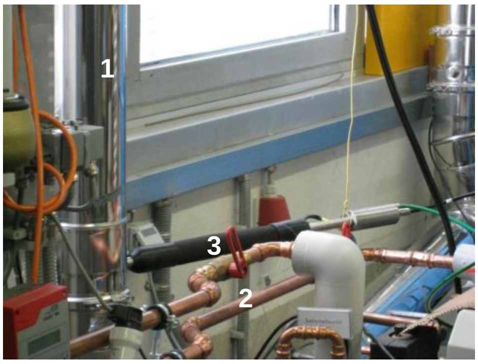

Figure 3: Sampling probe of the emission sampling system (ESS) connected to the stack.

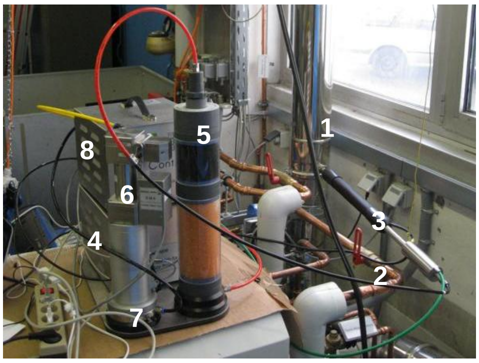

Figure 4: Complete setup consisting of sampling probe, dryer and filter for dilution air, control unit and SMPS+E for particle analysis. Legend: 1: Stack with exhaust gas, 2: Hydraulic connection and sensors, 3: Sampling probe, 4: Control unit, 5: Dryer and filter for dilution air, 6: M-DMA, 7: FCE, 8: DMA Controller

The particle number distribution was measured by use of a Scanning Mobility Particle Sizer with a Faraday Cup Electrometer (FCE) as counter, abbreviated SMPS+E. The complete system consisted of a FCE for particle counting, a Differential Mobility Analyser (DMA) for particle sizing, a DMA Controller and an Am241-neutralizer.

The sample volume flow rate was set to 1 l/min. Thus, in combination with the 9 l/min volume flow rate of the dried and particle free dilution air a dilution ratio of 1:10 was realized. The particle size distribution was measured online in 44 particle size channels for each scan.

In addition to the particle measurement, the following parameters of the exhaust gas were also measured with a ECOM J2KN multi-gas analyser and displayed by the software DASNT: CO [ppm], CO [mg/m3], O2 [%], Lambda [ ], Eta [%], T gas [°C], CO2 [%] and NO2 [ppm]. The multi-gas analyser is equipped with a condensate trap and a particle filter.

2.2 Experiment

10:00 am: setup SMPS+E, installation and warm up of the sample probe, preparation of the pellet burner with special slit burner cup, warm up of multi gas analyser
10:17 am: start particle measurement, measurement 1, complete scan with 44 size channels from 3,01 to 154,79nm in 48 seconds each
10:27 am: start multi-gas analyser
10:31 am: start burner, ignition, pellets dropping in (pellet balance start: 6,57kg)
10:36 am: warm up phase, CO-values increase
11:28 am: set up changes of pellet burner, reduction of pellet flow,
old: 15 + 15 (dropping time + delay in seconds), new: 12 + 15
11:33 am: set up changes: ventilation air,
old: 180, new: 170, annotation: maximum is 255 corresponding to 25,5 = 10%
12:07 pm: end of measurement 1
12:21 pm: set up change: SMPS+E, old: complete scan with 44 size channels from 3,01 to 154,79nm in 48 seconds, new: no scan, fixed size channel 47,12nm, with 4Hz
12:25 pm: start particle measurement, measurement 2
12:29 pm end of measurement 2
12:50 pm set up change: position of particle sample probe and multi-gas analyser in the exhaust stack, old: particles then gas, new: gas then particles
12:52 pm start particle measurement, measurement 3
13:05 pm end of measurement 3

2.3 Results

For the following discussion of the results of measurement 1 the dilution factor of 1:10 is included by the data acquisition software and applied to the raw data.

The change in particle size distribution is shown in figure 3. The concentration ranges are labeled with different colours. The warm up between 10:36 am and 10:50 am immediately after the ignition shows a significant difference in particle size. During warm-up the maximum of the size distribution is at about 100 nm. In the constant operation phase the maximum is shifted to between 40 – 50 nm. The maximum concentration both in the warm up and the constant phase is about 10^8 particles/ccm.

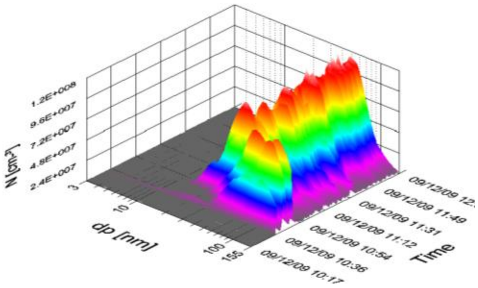

Figure 5: 3D-plot of the particle size distribution.

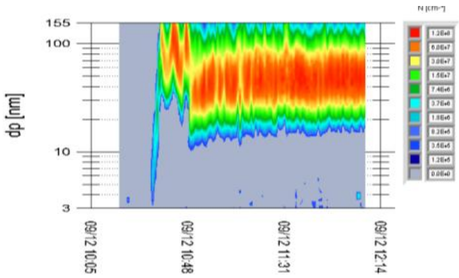

Figure 6: 2D-plot

The shift in particle size distribution down to smaller particle diameters between warm up and 15kW operation also can be seen in the 2D-plot, which is a top down view of the 3D-plot. The high time resolution of the SMPS+E system made it possible to measure the alternating emission pattern (figure 5+6) that is caused by the automated continuous feeding of the burner with fresh pellets every 15 seconds including delay time combined with the active CO-triggered ventilation.

To display the total number concentration, the concentrations in each of the 44 size channels in a single scan were summed up. These results are shown in figure 7.

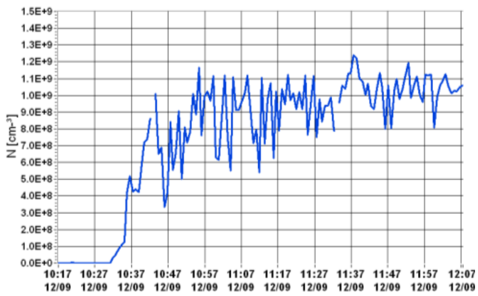

Figure 7: Time series of total number concentration

From the raw data the dust mass was calculated assuming spherical particles with a homogeneous density of 1,6g/cm³, that is typical for carbonaceous material. Temporal variation of the calculated dust mass is shown in figure 8, x-axis identical to figure 7.

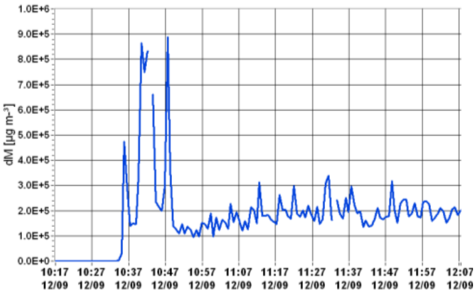

Figure 8: Time series of total mass concentration

As shown in figure 7 the total number concentration increased from 0.5 * 10^8 particles/ccm to over 10^9 particles/ccm. On the other hand the particle mass decreased from 800mg/m³ in the warm up phase to 200 mg/m³ during the constant 15kW phase, as shown in figure 8. Also the emissions from the pellet combustion remain relatively stable during constant operation.

An additional information provided by the fast SMPS+E scanning is the comparison of the normalised number and mass distributions at different operation phases. In figure 9 the number distributions are shown in the upper diagrams and the corresponding mass distributions in the lower diagrams. The left column provides data from the warm up phase and the right column from the constant 15kW operation. For the purpose of direct comparison the scales of the top and bottom diagrams are set to be identical.

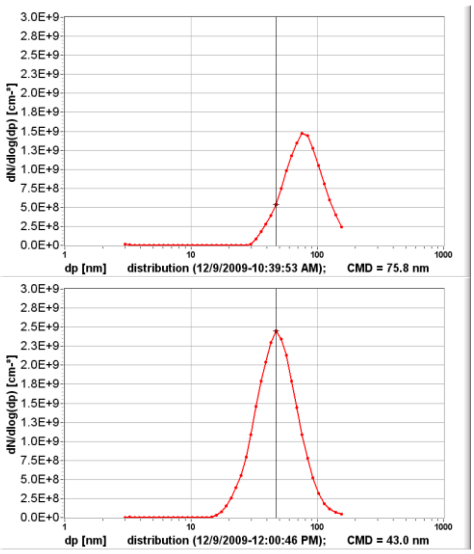

Figure 9: Comparison of normalized size distribution for the two different operation phases warm up (top) and constant 15kW (bottom)

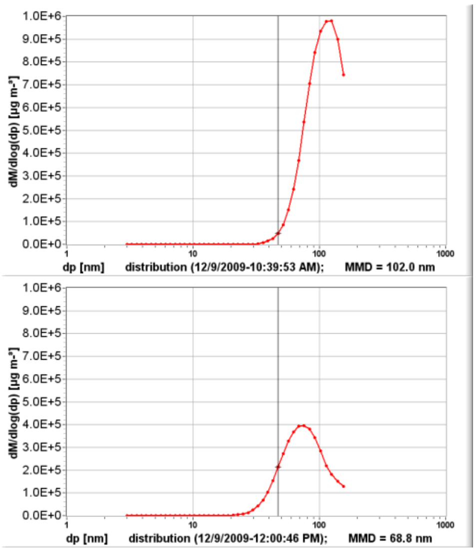

Figure 10: Comparison of normalized mass distribution for the two different operation phases warm up (top) and constant 15kW (bottom)

The LabView software used for the diagrams in figure 9 and 10 additionally displays the Count Mean Diameter CMD or the Mass Mean Diameter MMD on the bottom. Also the CCM are much lower compared to dust emissions from woodchips ([2] Klippel and Nussbaumer, 2007) these results agree with e.g. data for the design standards of ceramic filter for reduction of dust emission from biomass burning ([3] Adler and Kalisch 2009).

Next, the settings of the SMPS+E were changed to measure the number concentration at one fixed particle size (47nm) with 4 Hz (Figure 11). With these settings it was possible to monitor the particle emission of the fresh pellets dropping into the burner. The results show the strong variation of the number concentration of a single size from 6 * 10^7 to 1,2 * 10^8 particles/ccm.

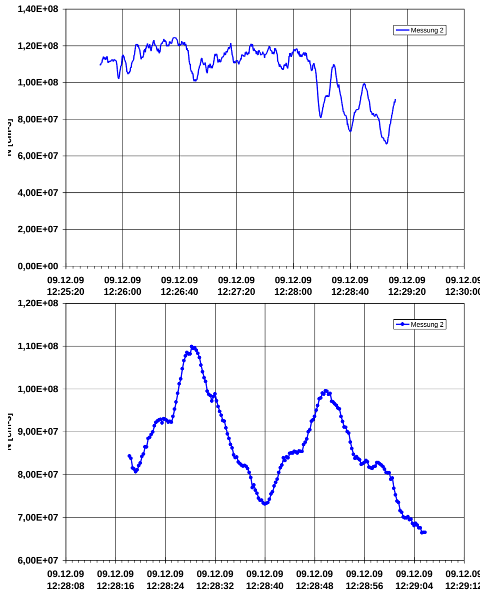

Figure 11: (Top) Temporal variation of the number concentration in a single size channel (47 nm) measured with a 4 Hz time resolution for 4 minutes. (Bottom) pellet feeding cycle, time series of the number concentration for a single size channel 47 nm with 4 Hz resolution

Zooming in, the right diagram in figure 11 shows the single pellet feeding cycles. During the 12 second feeding interval the number concentration increases to a maximum. In the following 15 seconds it decreases. Since now, such data have not been published.
A change of the sampling position in the stack showed no effect. Both the number and mass concentration have been exactly in the same range as measured before.
The additional data from the multi-gas analyzer are important for controlling the burner and deliver important information about the quality of the combustion. According to the focus of this study on particle emissions, the results of the gas analyzer will be discussed elsewhere.

The Grimm Emission Sampling System also has been tested for the determination of soot emissions in the 400°C hot exhaust after a diesel generator with and without filter. Therefore a butanol condensation particle counter , CPC without DMA was chosen, to measure the total number concentration in the size range between 5nm up to 2µm. These results, showing a very good filter efficiency of the filter elements up to 99%.
The same measurement setup was used for a third application, namely the determination of ultrafine particles in the exhaust of a gas turbine test rick. Results of this two applications will be shown in a brief overview at the presentation, only and published separately.
Results

2.4 Summary

A 15 kW test pellet burner was evaluated in regards to particle emission in preparation of an upcoming change in regulation. If the burner was operated incorrectly significant levels of particle emission were reached. The GRIMM emission sampling system in combination with a scanning mobility particle sizer allowed continuous online measurements of these emissions in the size range 3nm to 155nm with a resolution of 44 size channels. Single channel measurements can be performed with a time resolution of up to 4 Hz. The system is very robust, portable, and only needs a power outlet for operation, it is therefore ideal for process control and emission measurements.
The System also has been tested for the determination of soot emissions after a diesel generator with and without filter. Therefore a butanol condensation particle counter, CPC without DMA was chosen, to measure the total number concentration in the size range between 5nm up to 2µm. These results, showing a very good filter efficiency of the filter elements, will be shown in addition.

3 Literature

[1] BImSchV, 2010, Erste Verordnung zur Durchführung des Bundes-Immissionsschutzgesetzes (Verordnung über kleine und mittlere Feuerungsanlagen). Bundesgesetzblatt Jahrgang 2010 TeilI Nr. 4, www.bundesgesetztblatt.de.
[2] Klippel N., and Nussbaumer T., 2007, Wirkung von Verbrennungspartikeln. Bundesamt für Energie, Bern 2007, ISBN 3-908705-16-9.
[3] Adler J., and Kalisch A. 2009, Keramikfilter in der Abgasanlage zur Staubemissionsminderung von Biomassefeuerungsanlagen. Abschlussbericht FKZ:220-22-006, Fachagentur Nachwachsende Rohstoffe e.V..