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Field investigations of nanoparticle emissions from various biomass combustion systems

FIELD INVESTIGATION OF NANOPARTICLE EMISSIONS FROM VARIOUS BIOMASS COMBUSTION SYSTEMS

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ABSTRACT: Wood combustion processes produce smoke emissions, that are of concern to authorities and the public. Recent European studies claim airborne particulate matter (PM) smaller than 10 ~µm (PM10) as major respiratory irritants (*Air pollution and Health*, EC-APHEA I and II). The Swiss Federal Environment Protection Agency is acquiring emission factors on PM pollutants of various sources in order to establish strategies for aerosol abatement. The work carried out by the *Center of Appropriate Technology and Social Ecology* covered the investigations of typical wood fuel combustion systems in the field under real world conditions. This to cope with the lack of quantified PM emission factors and characterization in terms of particle numbers and size distribution.

Two analytical methods were used to monitor PM emissions. A *Scanning Mobility Particle Sizer* (SMPS) was utilized to determine nanoparticle numbers and size distribution in wood combustion stack gases with mobility diameter up to 0.6 µm (PM0.6). *Total Suspended Particles* (TSP) were measured simultaneously to compare TSP with the emissions of PM0.6, calculated from the SMPS-analysis.

There have been 14 different wood combustion systems tested including room heating appliances, wood log and automatic fed boilers. The wood based fuel comprised logs, chips and pellets. It could be shown that the major part of the particle sizes is in the range of 30 to 300 nm. Particles >300 nm do not add much to the total emission rate in the flue gases. The particle distribution of manual operated appliances varies quite during a burn cycle, while wood log or continuos fed boilers show a fairly constant particle size distribution. The minimum emission factor of total particle number (TNPM0.6) of the different combustion systems was found in the range of approximately 1:3.6, where as the maximum spread widely. The TSP emission factors correspond with the TSP figures calculated from SMPS data if there were little products of incomplete combustion (PIC) and no high grate vent entraining ash. The data acquired with this project allows prediction of the PM on a particular airshed of a population of different wood combustion systems.

There have been six fossil plants analyzed for comparison. The plants comprised typical representatives of boilers and co-generation units. The average emission factor for total particles number was of the factor 16 lower compared to the one of the wood combustion systems.

Keywords: wood combustion, particulate matter, emission factor, field measurement

1. INTRODUCTION

There is a growing interest for biomass fuels to cover a larger part of the required energy supply. Solid fuel burning combustion systems produce smoke emission, which are of concern to authorities and the public. Recent European studies claim airborne particulate matter (PM) smaller than 10 ~µm (PM10) as major respiratory irritants (*Air pollution and Health*, EC-APHEA I and II). Because of the small size of the particles (typically of the order of 1 micron and less) they easily pass through the nose and throat into the lungs [1]. The Swiss clean air act limits on air quality in form of limits on the suspended particulate matter (PM10) allowed in the atmosphere. In turn, authorities use these regulations to place limits on airborne particulate matter allowed from emissions sources in areas, which suffers from air pollution. The Swiss Federal Environmental Protection Agency requires emission factors on PM pollutants of various sources in order to establish strategies for aerosol abatement. Several research institutes are presently investigating nanoparticle emissions from traffic such as vehicles or railroad. Nanoparticle emissions from wood burning processes have not yet been measured under real world operating conditions, although these particle fractions can be relevant for health reasons in local areas.

2. OBJECTIVES

The work carried out by the *Laboratories for Sustainable Energy Systems* at the Center of Appropriate Technology and Social Ecology covered the investigation of typical wood fuel combustion systems in the field under real world conditions. The aim was to quantify PM emission factors and characterization in terms of particle numbers and size distribution in order to cope with the lack PM emission data.

The following wood combustion system were tested:

- Batch-wise fired appliances with manual refueling of wood logs comprising room heaters (2) and heat accumulating stoves (2).
- Batch-wise fired boilers with manual refueling of wood logs (2).
- Automatically fired wood pellet burners as boilers (2) and as room heater (1).
- Automatically fed wood chip burner with stoker (2), movable grate (2) and a gasifier (1).

3. EXPERIMENTAL

3.1 Total suspended particles (TSP)

The method to measure *total suspended particles* (TSP) was in accordance with the ISO/DIS 13336 [2] applying disk filters (figure 1).

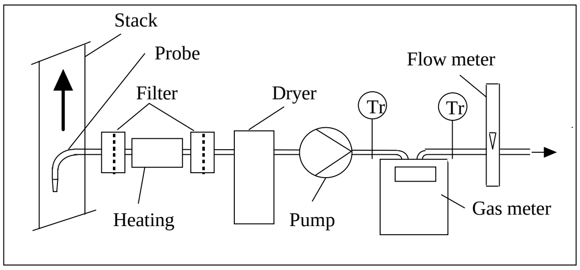

Figure 1: Equipment for the measurement of *total suspended particles* (TSP) according to ISO/DIS 13336 [2].

The particle mass was determined by gravimetric analysis of the dried filters.

3.2 Nanoparticle analysis

Samples were previously diluted with hot particle free air by a rotating disk containing 10 circular caveties (Matter-Diluter MD-19). The speed of that disk was adjusted to a resulting dilution factor of 200, which prevent condensation of water onto the particle surface by lowering the dew point below ambient temperature.

A s*canning mobility particle sizer* (SMPS, TSI Model 3936) was applied to analyze *size distributio*n and *total number concentration* (TNC) of nanoparticles within the range of 0.01-0.600 µm [3]. An impactor with a cut-off d_{50} of 0.690 nm was used to withdraw the coarse particle fractions. The polydisperse aerosol particles in the sample gas (0.4 l/min) passed through a KR-85 bipolar charger, establishing a bipolar equilibrium of the particles. The particles then entered the *differential mobility analyzer* (TSI, DMA 3081) where they were separated on a laminar shield flow (4 l/min) according to their electric mobility. A subsequent *condensation particle counter* (TSI, CPC 3010) evaluated the number concentration of the monodisperse aerosol particles. The number size distribution was measured by varying the DMA voltage over the measuring range (up 240 sec; down 60 sec) and by recording the accompanying particle concentrations with the CPC. This scanning method was controlled by computer software (TSI, Vers. 3.2). The analytical set-up is shown in figure 2

The characteristic data of particles are given by the *mode diameter* (MD) as the most frequent size of a particle population and the *total number concentration* (TNC) as the total amount of particles over the whole measured range.

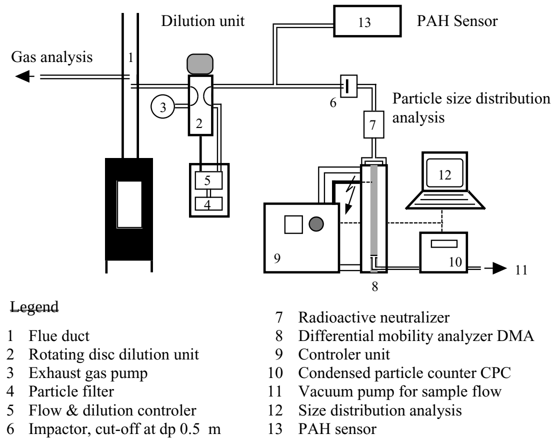

Figure 2: Analysis of nanoparticles with *scanning mobility particle sizer* (SMPS).

The particle distribution graphs are done as commonly used in aerosol measurement: the channel width, which represents *particle diameter* (dp) range, is plotted on a logarithmic scale against the *total number concentration* (TNC), that is calculated from the measured number of particles (dN) divided by the logarithm of the channel width (dlog(dp)), where dp is the mobility diameter.

3.3 Test environment

The wood log and automatically fed boilers have been tested on site. The room heating appliances were tested at the *Laboratories of Sustainable Energy Systems*. The lab infrastructure eases repeatable test conditions by applying accurate platform scale to measure the burn cycle of a wood log batch.

3.4 Wood combustion systems

The tested wood combustion systems had following technical specifications:

- *Roomheaters, batch-wise fired with wood logs:*
  Two different designed appliances have been tested. One appliance was a cast iron construction (**A**) the other was a welded construction (**7**). Both had a door with glazing for a visible flame.
- *Heat accumulating stoves:*
  Two heat accumulating appliances were tested: one appliance was made from tiled masonry (**8**) the other from soapstone (**B**).
- *Wood log fired boilers:*
  Two different boilers with a heat output of 25 kW (**5**) and 70 kW (**6**) were tested. The logs were air dried with a water content of 20 % (b.d.).

- *Wood pellet burners with mechanical feed:*
  Two different boilers with a heat output of 17 kW (**C**) and 25 kW (**9**) were tested. A pellet fed appliance for room heating with heat output of 10 kW (**10**) was also investigated.
- *Wood chip burners with mechanical feed (stoker type):*
  Two mechanical fed boilers were measured with 70 kW (**D**) and 200 kW (**1**) heat output for dry chips with a water content of 30 % (b.d.).
- *Wood chip burners (moving grate) with mechanical feed:*
  Two boilers have been tested with a heat output of 325 kW (**2**) and 800 kW (**3**) for green chips with a water content of 54 and 65 % (b.d.).
- *Wood burner (gasifier) with mechanical feed:*
  The boiler was connected to a gasifier to burn wood residuals of a saw mill (**4**) The heat output was in the range of 200 kW. The residues were dry with a water content of 10 % (b.d.).

3.5 Test procedure

The TSP and particle size measurements were done simultaneously in the stack. The measurements at the appliances were done over several burn cycles. The test period of the *batch-wise burning appliance* commenced with the refueling of a new batch to the ember. When the platform scale read the initial weight the test cycle was stopped.

The test period of the *heat accumulating stove* started with the ignition of the fuel. The particle sampling ended when the carbon dioxide in the flue gas was below 2.5 Vol%.

The burn cycle of the wood log boilers lasted several hours. Different Samples were taken over one burn cycle. The mechanically fed boilers were tested over their various operating cycles like full load, part load and ember phase with no load.

4. RESULTS

The particle number distribution of the batch wise fired appliances are varying quite during the burn cycle. A typical particle distribution over a burn cycle is shown in figure 3. The start-up phase shows large particles with a mode diameter of 160 nm. In the phase where the stove is in its full operation, there is a bimodal behavior with a mode at 15 and 50 nm. In the burn-out phase the particle size is increasing again to mode diameter of about 90 nm.

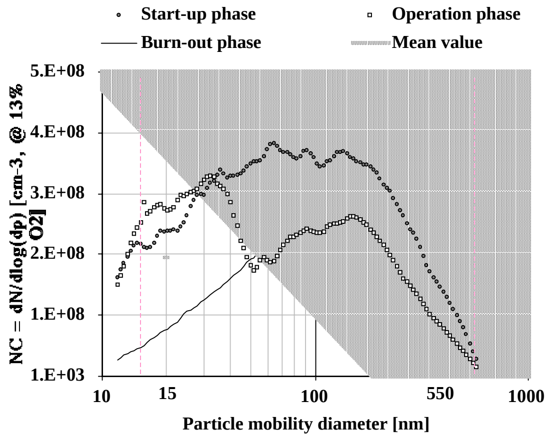

Figure 3: Typical particle size distribution over a burn cycle of a batch wise fired appliance (heat accumulating stove (**8**).

The particle number distribution of wood log and automatic fired boilers are much more even over their burn cycles. A typical particle size distribution is shown in figure 4 (pellet boiler **C**).

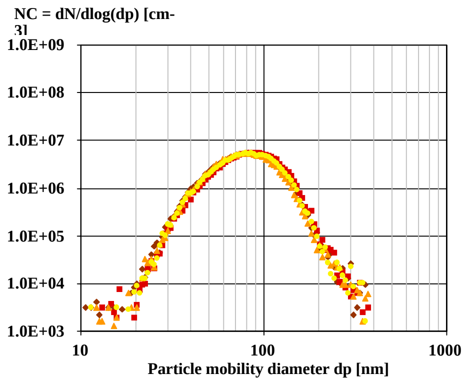

Figure 4: Typical particle size distribution of a pellet boiler **(C)** at nominal heat output.

The total emissions rate of particle fraction < 600 nm can be estimated from SMPS-data assuming spherical particles and a density (estimated 1500 kg/m^3). The particle mass fractions and the accumulated particle mass are shown in figure 5. The graph of the accumulated particle mass flats out at 200 nm. It can be concluded that particles above 300 nm do not add substantially to the total particle emission rate.

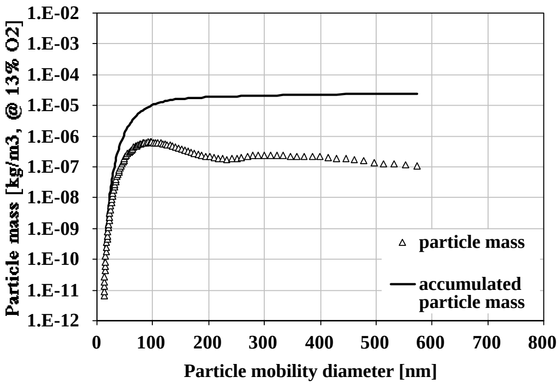

Figure 5: Pellets boiler (**9**): Particle mass in each fraction and accumulated particle mass over all fractions assuming particle shape as spheres with a density of 1'500 kg/m^3.

The effect of excess air on the particle formation was investigated for a wood chip boiler. The results are shown in figure 6. Not only the number of particles depends on the oxygen content, but also the mode diameter. At lower oxygen content fewer particles are formed. The most frequent diameter changes from approx. 60 nm at 11.6 % O_2 to approx. 87 nm at 2.7 % O_2.

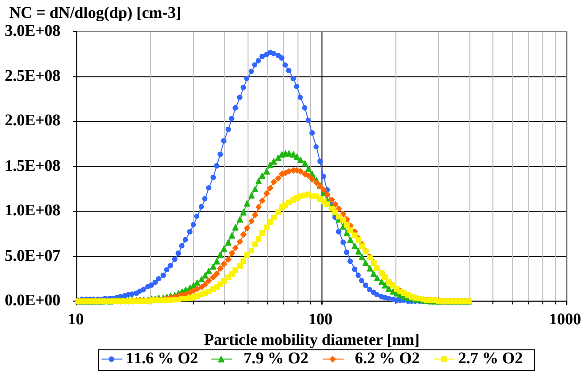

Figure 6: Particle number concentration as function of excess air (Wood chip boiler **D**).

The emission factors of the TSP-values measured by flat filter method and the calculated PM0.6-emission factors by SMPS are compared in figure 7. The TSP emission factors correspond with the TSP figures calculated from SMPS data if there were little products of incomplete combustion (PIC) and no high grate vent entraining ash.

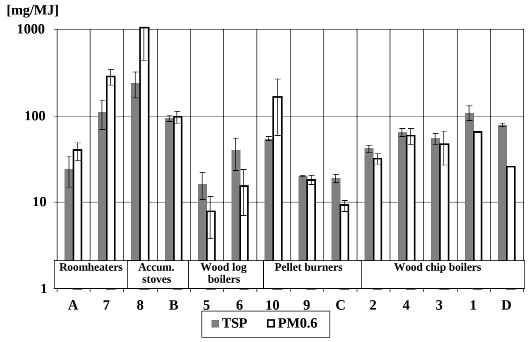

Figure 7: Emission factors of TSP, measured with disk filter in the flue duct and in the dilution tunnel versus TSP, calculated from SMPS-values.

The results of the investigations are summarized in Table 1.

Table 1: Summery of particle measurements

	Total suspended particles TSP		Nanoparticles PM0.6	
Method	Disk filter		SMPS	
	TSP-Emission[1)]	Emission factor	Emission factor PM0.6	TN- emission factor TNPM0.6
Dim.	[mg/m$_n^3$]	[mg/MJ]	[mg/MJ]	[#/MJ]
Roomheating appliances				
Roomheaters	99 ± 36	68 ± 25	161 ± 29	5.4 ± 1.5 E13
Accumulating stoves	247 ± 45	167 ± 44	569± 309	15.4± 6 E13
Wood log boilers				
Boilers	42 ± 17	28 ± 11	12 ± 6	6.0 ± 1.7 E13
Pellet burners				
Boilers	29 ± 1.7	20 ± 01.2	14 ± 2	2.7 ± 0.2 E13
Roomheater	80 ± 4	54 ± 3	164 ± 105	8.6 ± 2.2 E13
Wood chip boilers				
dry fuel	140 ± 18	94 ± 13	45 ± 1	9.2 ± 0.9 E13

wet fuel	67 ± 8	48 ± 6	39 ± 12	4.9 ± 0.5 E13
residuals	96 ± 11	64 ± 7	59 ± 12	8.2 ± 0.7 E13

1) based on 13 % oxygen

There have been six fossil plants analyzed for comparison. The plants comprised typical representatives of boilers and co-generation units. The fuel was natural gas (NG) and petroleum (oil). The petroleum boiler had a heat output of 465 and 1165 kW, the co-generation unit 70 kW eletcrical and 90 kW thermal output. The gas boiler delivered some 190 kW and the two co-generation units 4.7 kW electrical and 12. 5 kW thermal resp. 15 kW electrical and 50 kW thermal.

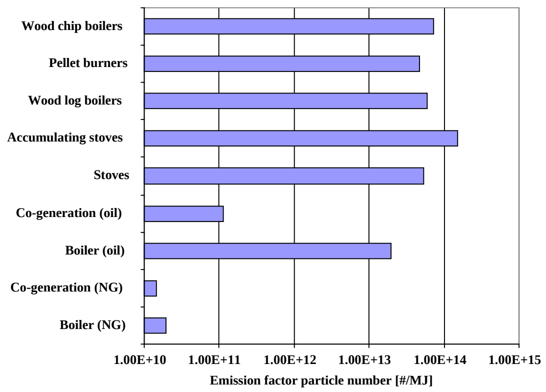

Figure 8: Emission factors of particles number < 600nm mobility diameter of wood and fossil combustion systems.

5. CONCLUSIONS

- The data acquired with this project allows prediction of the particulate matter emissions on a particular airshed of a population of different wood combustion systems.
- The results show that the major part of the particle emissions (up to 95%) are smaller than 0.3 µm.
- The particle size in the exhausts of wood fired appliances is in the range of 50 to 200 nm. The range of wood log or automatically fired boilers lays between 70 to 120 nm.
- The most frequent size of the particle number concentrations for batch operated appliances is approx. 100 nm, whereas the particle distribution changes quite a lot during the burn cycle. The particle size distribution for wood log and mechanically fed boilers remains constant and shows a most frequent size of the particle number concentrations of approx. 80 nm.
- The minimum PM0.6-emission factors of total particle number of all categories spread about 1:3.6 (2.5 ÷ 9 E13 #/MJ). The maximum thus varies widely.
- There is an influence of fuel and operating parameter. The variation of particle numbers due to load variation is ± 15 %.
- With the fractions of particle number concentrations and some assumptions on particle geometry and density one can estimate the particle emission rate from SMPS data.
- The TSP emission factors correspond with the PM0.6-emission factors calculated from SMPS data if there were little products of incomplete combustion (PIC) and no high grate vent entraining ash.
- The particle size distribution graph allows a quick qualitative judgement of smoke emissions.
- It can be concluded that the SMPS method is a feasible on-line method to analyze nanoparticles from wood combustion processes under real operating conditions.
- The average emission factor of total particle number for fossil fuel combustion system was of the factor 16 lower compared to the one of the wood combustion systems.

ACKNOWLEDGMENTS

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