

Status of PM emission measurement methods and new developments

Technical report

Claudia Schön and Hans Hartmann



A sampling nozzle removed from a flue gas duct after collection of particulate matter
Photo: TFZ

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with contributions from several IEA Task 32-members and other experts

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Preface

Accurate determination of particulate matter emission (PME) from solid fuels is an ambitious task which is quite insufficiently assisted by technical standards, as they are sometimes inadequate or not sufficiently comprehensive. In this vast field of many methods and high diversity of measurement devices there is still too much room for interpretation and adaptation of procedures. Thus, researchers and testing bodies often have to create their own rules for good laboratory practice, sometimes assisted by internal validation routines. But results from such internal quality assurance efforts are usually never disclosed, if at all documented. Furthermore, the target audience for emission measurements is usually more fascinated by the actual results than by the way these results are generated, and this audience is simply not aware of the manifold uncertainties which can sometimes make spectacular scientific findings doubtful. This is why actions on method development, their onward elaboration or international harmonization need to struggle for attention or institutional support.

By nature, there is thus an immanent lack of information on quantitative effects on measured PM emission. This deficit was tackled when a group of European research institutions decided to form a temporary and quite loose network, the "EN-PME project". This project made use of existing nationally funded programs to focus on joint activities towards a common goal, the elaboration of a harmonized European PM determination method. This EN-PME Network with 15 partners from 10 European countries was coordinated by INERIS/France and by CATSE/Switzerland. Among other actions, it enabled an exchange of existing or still to be created technical knowledge on method performance which forms a basis of this IEA report.

But further knowledge and experience was collected via a specific questionnaire which had been sent out to the members of IEA Task 32 (Combustion) and their national partners. This questionnaire aimed at providing published or unpublished documentation about experience on influencing factors on measurement accuracy. As a result, the response from 7 institutions from 6 countries is regarded and compiled in this report.

However, it can be assumed, that much relevant information is yet undiscovered, and thus the impacts and effects displayed in this report remain fragmentary. In view of growing market integration and internationally harmonized environmental goals, a continued discussion and common international approach towards harmonizing measurement methods is more than ever required in the future.

Abbreviations for names of institutions mentioned in this report

BIOS – BIOS Bioenergiesysteme GmbH, Graz, Austria
CATSE – Centre of Appropriate Technology and Social Ecology, Switzerland
CTSB – Scientific and Technical Centre for Building, France
DBFZ - Deutsches Biomasseforschungszentrum, Leipzig, Germany
DTI – Danish technology Institute, Denmark
FHNW - Fachhochschule Nordwestschweiz, Windisch, Switzerland
INERIS – French National Institute for Industrial Environment and Risks, France
LERMAB – University of Nancy, Laboratory for Studies and Research on Wood Material, France
SP – Technical Research Institute of Sweden (now renamed to "Rise"), Gothenborg, Sweden
TFZ – Technology and Support Centre, Germany
UEF – University of Eastern Finland, Finland
VSB-TUO – VSB Technical University of Ostrava, Energy Research Center, Czech Republic

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1 Introduction

1.1 Problem definition

Particulate matter emissions (PME) from biomass combustion have always been in the focus of air pollution control. And attention is still rising while regional or international emission limits tighten and requirements defined in international product standards become stricter. Furthermore, particles discharged from solid fuel burning appliances and boilers usually contain soot and organic components which are known for their potential to be specifically harmful for health and environment. Due to their small size (mostly below 1 μm aerodynamic diameter) they can easily pass through the nose and throat into the lungs. Additionally, many such PM-enriched flue gases also carry organic gaseous carbon species (OGC) which act as precursors for secondary organic aerosols (SOA). Via photo-oxidation under the influence of UV-radiation these organic species can also contribute to the total PM concentration in an atmosphere.

However, to evaluate the magnitude at which a biomass based PME source contributes to atmospheric pollution is not an easy task. Many different methods have historically been used to measure PME from the flue gas of residential appliances and boilers for biomass (mostly wood). Confusion has arisen in the market as different and conflicting results are quoted in literature and test reports. Even within Europe, where common market rules should apply, several national measurement standards are living side by side, and compatibility of reported PME levels is not given. In a worldwide consideration such differences are even higher, and manufacturers cannot access new markets without providing additional test results based on the respective measurement standard applied in the region.

But even where there is an agreement about using a specific test standard, there is usually still quite some room for its interpretation. Knowledge about the impact of given variation concerning suitable measurement equipment, the materials used, or the operational settings during a test is quite low, or at least little attempt has yet been made to compile such knowledge as a basis for further specification of measurement rules. And beyond these difficulties there is one more challenge: Other than for measurements of gaseous emissions, PME measurements suffer from the fact that there is no system for calibration which could validate the full PM-sampling and measurement process under realistic conditions. Therefore, uncertainty about research data for PME is always relatively high.

1.2 Aim of this report

It is the aim of this report to stimulate an international approach towards one (or few) method(s) for determining particle emissions from biomass based combustion. Thereby, the focus is set only on the actual PM-measurement technique while disregarding the way how an appliance is operated during a test. This goal is approached by three key activities:

- to provide an overview on the diversity of existing measurement strategies in order to emphasize the need for a harmonized approach;
- to provide knowledge on the influence of method variations (e.g. equipment, test rig design, operational parameters, materials used, deposits, etc.) on measured PME results. Where possible, quantitative results from published and unpublished documents are cited and
- to present and to describe the recently developed EN-PME method which was suggested as common European measurement strategy. This is to raise discussion about its suitability for an international approach within and beyond European boundaries.

1.3 Particle formation pathways

From the moment when gaseous, liquid and solid compounds are created during combustion until their appearance as particulate matter in atmosphere, particles and their precursors pass through several stages of transformation which need to be understood in order to evaluate possible impacts on the chosen measurement method. Therefore, this chapter shall provide the basic knowledge.

An overview of PM formation pathways in flue gas and ambient air is summarized in Figure 1.

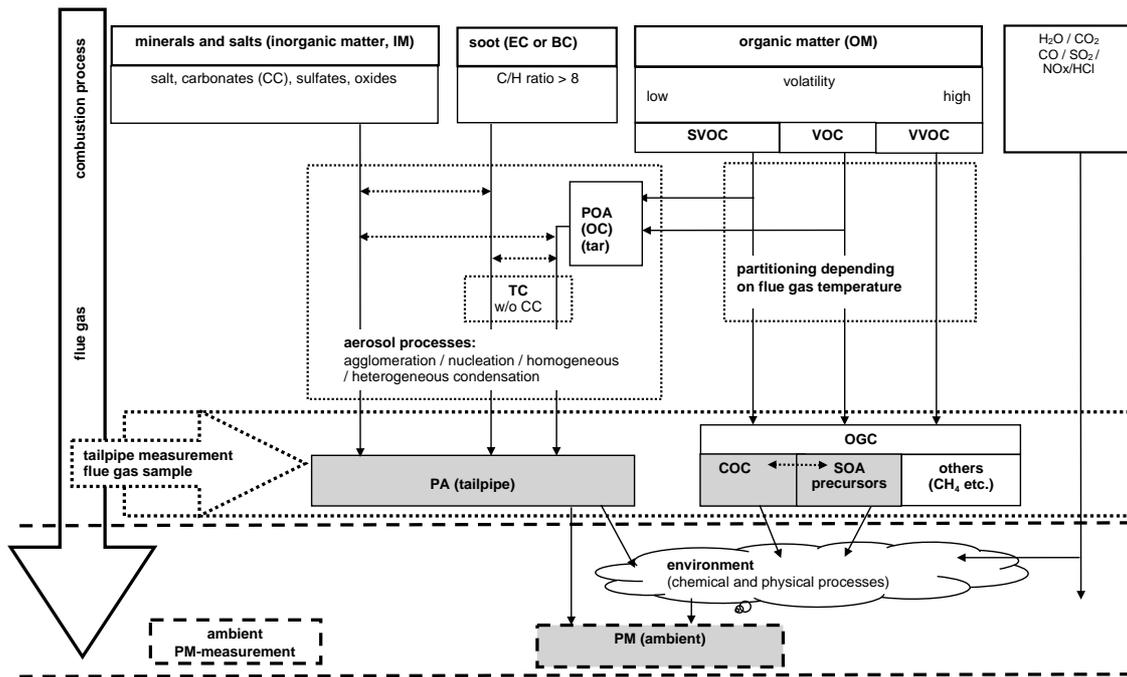


Figure 1: PM formation pathways in flue gas and ambient air and classification of products. Graph developed by Christian Gaegauf (CATSE) with input by DBFZ, TFZ and other partners within EN-PME Test. The abbreviations used are defined in Table 1

Table 1: Definition of the acronyms in Figure 1.

Acronym	Term	Remark
BC	black carbon	soot fraction of particulate matter emissions (identical EC)
CC	carbonates	carbonates formed from ash components and carbon in fuel
EC	elemental carbon	soot fraction of particulate matter emissions (identical BC)
IM	inorganic matter	minerals and salts (carbonates, sulfates, oxides, etc.) as inorganic fraction of particulate matter emissions
NMOGC	non-methane organic gaseous carbon	potential SOA precursors
OC	organic carbon	organic carbon fraction of particulate matter emissions resulting from incomplete combustion
OGC	organic gaseous carbon	
OM	organic matter	tar, SVOC, VOC, VVOC, OGC
PA	primary aerosols	salt, minerals, soot, tar, SVOC, VOC, VVOC released with the flue gas as solid or condensed particulate matter to the atmosphere (identical PME)
PM	particulate matter in ambient air	
PME	particulate matter emissions	PME = PA, solid and condensed particulate matter in the flue gas (identical PA)
POA	primary organic aerosols	organic fraction of PME
SOA	secondary organic aerosols	OGC transformed in the atmosphere to particulate matter as a result of UV exposure
soot	elemental carbon	soot (C/H > 8), carbon particles fraction of particulate matter emissions resulting from incomplete combustion (identical EC or BC)
SVOC	semi volatile organic compounds	boiling range: > 250 °C
tar	tar	condensed low volatile organic compounds
TC	total carbon	carbonaceous particle fraction of particulate matter emissions TC = EC + OC (without carbonates, CC)
VOC	volatile organic compounds	boiling range: 100 – 250 °C
VVOC	very volatile organic compounds	boiling range: < 100 °C

One important parameter regarding the determination of particle emission is the temperature dependency of the condensation processes of organic aerosol forming elements in the flue gas duct. Figure 2 illustrates schematically the temperature dependent behaviour of particle forming elements after passing the flue gas socket of a boiler or stove. Particle forming elements originating from inorganic aerosols and heavy metals (KCl, K₂SO₄, K₂CO₃, ZnO, etc.) as well as soot are not affected by the flue gas cooling. But other organic gaseous compounds can be grouped into three categories each describing a different behaviour during flue gas cooling.

- *Methane and other none-condensable compounds.* They will not contribute to particle formation.
- *Condensable organic compounds.* They do contribute to particle formation as lower flue gas temperatures forming the so-called primary organic aerosols (POA). This process occurs in the flue gas duct and in the chimney.

- *Secondary organic aerosol precursors.* They are compounds that form particles after leaving the chimney into the atmosphere by formation of secondary organic aerosols (SOA) which will not be determined with the particle determination method considered in this report.

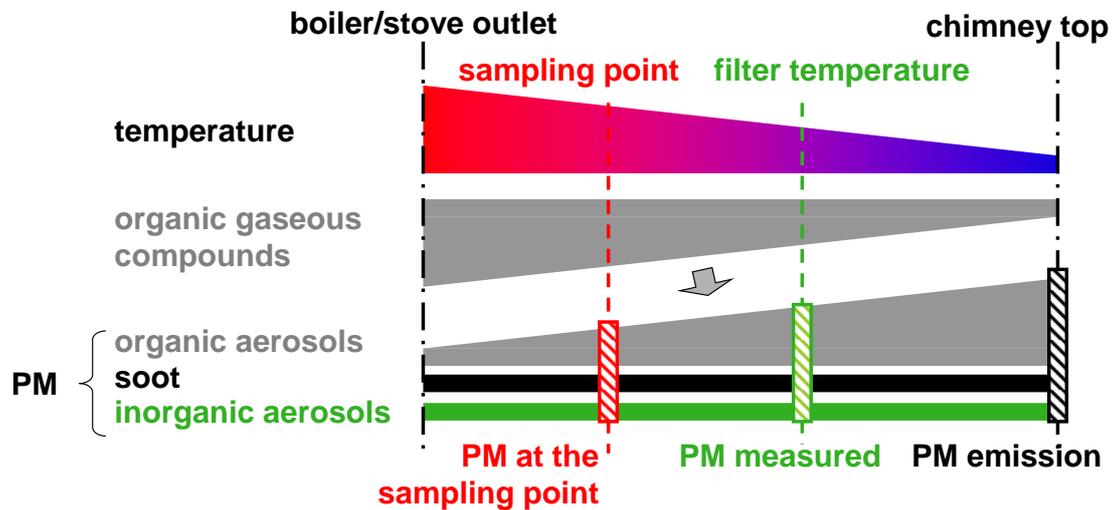


Figure 2: The influence of the flue gas temperature on the measurement of primary PM emissions (Source: T. Brunner, BIOS, UltraLowDust-Project)

No number concentration measurements will be discussed in this paper.

2 Overview of existing PM determination standards and methods

Worldwide there are different methods available for the determination of particulate matter (PM) emission. These methods include

- determination (sampling) in the hot flue gas,
- determination (sampling) in the diluted (cooled) flue gas and
- determination via electrostatic precipitators which are integrated in the hot flue gas section in order to achieve complete PM collection from the full flue gas flow for gravimetric mass determination.

In this chapter an overview of existing European and International Standards regarding the determination of PM is given while differentiating between determination in the hot flue gas and the diluted flue gas. Only in the United Kingdom the PM emission is determined via electrostatic precipitator following the British Standard PD6434 [1] this method shall not be further discussed here.

2.1 PM Sampling in the hot flue gas

During the combustion of solid biofuels in stoves or boilers flue gases are emitted at elevated temperatures depending on the technology applied. In some countries, the particulate matter emission is directly determined in the hot flue gas without any further treatment of the flue gas itself. Special measurement sections are installed in order to make sure that a representative sample is withdrawn from the flue gas.

United States. In the United States the method described in US EPA Method 5H [2] is applied for wood heaters from a stack location. This method includes the following boundary conditions.

- The flue gas sampling is done against the flue gas flow with a nozzle orientation of 180° (i. e. with nozzle opening pointing upstream).
- Use of two glass fibre filters where the first filter has a temperature below 120 °C and is followed by a series of impingers and the second glass fibre filter is kept at temperatures below 20 °C in order to collect also the condensable fractions of PM.

No further specification on filter treatment procedure or issues regarding isokinetic sampling is made.

Germany and Austria. For measurements at test stands the VDI directive 2066-1 [3] is mostly referred to. It describes the gravimetric determination of dust loads applied in Germany. The following boundary conditions are specified.

- Isokinetic flue gas sampling is done parallel to the flue gas flow with a nozzle orientation of 180° (i. e. with nozzle opening pointing upstream). Only one plane filter is used. The inner diameter of the nozzle shall be 8 mm at minimum. At high dust load also a stuffed cartridge can be used.
- The filtration temperature during PM sampling shall be at 160 °C.

- The pretreatment of the filter media is set to 180 °C while the filter media has to be thermally treated after sampling at 160 °C, always for 1 hour, and then be stored in a desiccator for at least 8 hours.
- The plane filter should be made of quartz fibre or in cases of low SO₃ concentrations in the flue gas also glass fibre filters are suitable.
- The filter media retention has to be 99.5 % on a test aerosol with a mean particle diameter of 0.3 µm (or 99.9 % on a test aerosol with 0.6 µm mean diameter).
- The deposition in the probe is collected via rinsing with water (twice) and acetone (once). The mass of dry deposits shall be added to the mass collected on the filter.

European method (draft). The final draft of the European Standard FprEN 16510-1 [4] is a comprehensive document for testing residential solid fuel burning appliances. Apart from the method mentioned above it also describes an alternative method for particle emission determination in the hot flue gas. The main specifications are as follows.

- Flue gas sampling from constant flow is stated and it should be withdrawn using a nozzle having an orientation of 180° (i. e. with nozzle opening pointing upstream) while only one filter is used. The inner diameter of the nozzle shall be 10 mm.
- The filtration temperature during PM sampling shall be at temperatures of minimum 70 °C and maximum 160 °C.
- Before weighing the retrieved filter media shall be thermally treated (dried) at a temperature level which is 35 K higher than the filter holder temperature during sampling (but not more than 180 °C). The duration of the thermal treatment is 1 hour. Then the filter is stored in a desiccator for at least 4 hours before weight determination.
- It is recommended to use quartz fibre filter (which does not contain any organic binders). If more than 100 mg/m³ on PM is expected a quartz wool pre-filter can be used additionally.
- The filter media retention has to be 99.95 % on a test aerosol with a mean particle diameter of 0.3 µm.
- There are some suggestions on the probe specifications itself. The internal diameter should be at approx. 8 mm and should have a maximum length of 1000 mm.
- Deposits in the probe are removed by washing the filter holder with acetone once a day. However, the mass of these deposits is not determined and thus not considered as total PM collected.
- In addition to PM measurement, the determination of OGC in the hot flue gas is required which is important if qualitative comparisons with measurements in the diluted flue gas at "poor" combustion situations are performed.

Table 2 summarizes the main differences of the methods for PM determination in the hot flue gas.

Table 2: Overview of PM determination in the hot flue gas

Standard	VDI 2066-1 (Germany & Austria)	US EPA Method 5H (USA)	FprEN 16510-1 (suggested for Europe)
Nozzle orientation	180°, against gas flow	180°, against gas flow	180°, against gas flow
Nozzle size	At least 8 mm	Not stated	10 mm
Isokinetic sampling	Yes	Not stated	Not stated
Filter material	Quartz fibre or glass fibre stuffed quartz wool cartridge at high dust load (above 50 mg/m ³)	Glass fibre	Quartz fibre filters; if more than 100 mg/m ³ use a quartz wool pre filter
Filter retention	99.5 % für 0.3 µm und 99.9 % für 0.6 µm	Not stated	99.95 % with a mean particle diameter of 0.3 µm
How many plane filters?	1 plane filter At high dust load: additional stuffed cartridge	2 plane filters	1 plane filter
Diameter of plane filter	instack (50 mm), outstack 50-150 mm	Not stated	Not specified
Filtration temperature	At least 160 °C	First filter at below 120°C, second filter below 20°C, impingers below 20°C	Maximum of 160°C
Temperature at filter treatment	Pretreatment at 180°C for 1 h, after treatment at 160°C for 1 h, always storage in desiccator for at least 8 h		180°C for 1 h and at least for 4 h in desiccator
Rinsing considered?	Yes, done twice with water and once with acetone. Mass of deposits is regarded as PME	Not stated	Yes, with acetone, but mass of deposits is not regarded

2.2 PM sampling in the diluted flue gas

In some countries the particulate matter emission is not to be determined in a hot flue gas because some of the organic components may not be condensed at elevated sampling temperatures and could therefore pass the filter in gaseous state. In this case the OGC determination is an essential part of the PME measurement. Flue gas dilution is therefore applied to achieve cooling and condensation, this is typically done by diluting with filtered air. Mostly this will cause a temperature drop to a level below 52 °C, thus transforming the flue gas into a state which comes closer to conditions as prevailing at or behind the chimney outlet. Consequently, such cooling of the flue gases will result in higher PM emissions measured, compared to the hot flue gas sampling, especially at more incomplete combustion.

In principle, flue gas dilution can either be performed by full flow or by partial flow dilution. Partial

flow dilution is a process where a small portion of flue gas is mixed with dilution air before the mixture is being conducted over a filter media for measurement. In full flow dilution the complete flue gas is diluted prior to the sampling of flue gas. Full flow dilution is usually required in standard measurement procedures, while partial flow dilution is applied for research purposes or for field measurements, where a full flow dilution cannot easily be realized.

A possible experimental setup using a dilution tunnel for full flow dilution is shown in Chapter 3 (Figure 3). Typical diameters of a dilution tunnel range between 150 to 300 mm.

Apart from the full flow dilution also different methods using partial flow dilution are available on the market, mainly for research purposes. There are different partial flow diluters such as the ejector diluter, perforated tube diluter, rotating disk diluter, concentric tube diluter, porous tube diluter and combinations, and they are further described by MIETTINEN et al. [19]. Some parameters of interest such as dilution ratio, residence time or dilution temperature were also studied and summarized by MIETTINEN et al. [19] without any main conclusions. In most studies a moderate dilution ratio of below 40 was applied leading to higher PM emission compared to the measurements performed in the hot flue gas. The optimum dilution system strongly depends on the focus of measurement which is typically a research issue on health and environmental aspects using partial flow dilution systems. Due to the fact that no systematic evaluation of the different systems has been done, the only method described in standards is the full flow dilution tunnel, which introduces disadvantages as the large space requirement or the relatively high construction and maintenance costs; furthermore they are not suitable for field testing. For the full flow dilution no influence on PM emission was observed at various sampling conditions (dilution ratio, sampling temperature and dilution tunnel residence time) [20].

Norway. Norway is one of the European countries that require the PM emission to be determined in the diluted flue gas, following a Norwegian Standard Method NS 3058-2 [5]. The main specifications are as follows.

- The partial flow sample is taken isokinetically from the dilution tunnel with a nozzle orientation of 180° (with nozzle opening pointing upstream).
- The temperature during PM sampling shall be below 35 °C.
- The filter media is made of glass fibre and shall be stored in a desiccator for at least 24 hours at ambient temperature, and it shall have a nominal pore diameter of 1.0 µm.
- In the sampling train, two plane filters are used in series for PM determination and their diameter is approximately 100 mm. Filters are positioned not more than 100 mm apart from each other.
- Deposits in the probe are considered as PME and are quantified. Therefore, the filter holders are washed and brushed with acetone for at least three times.

Australia/New Zealand. In both countries a dilution tunnel is used. It is described in the Standard AS/NZS 4013 [6]. The main specifications are as follows.

- A partial flow is taken using a nozzle orientation of 90°; no specifications are made concerning the sampling speed.
- The temperature of the sampling train during PM determination shall be between 15 and 32 °C.
- The temperature in the dilution tunnel has to be above 25 °C.

- The filter media shall be desiccated for 24 h at ambient laboratory temperature and pressure.
- The filter media is made of glass fibre and has a diameter of 50 mm. The collection efficiency is above 99.95 % on 0.3 µm particles.
- Two plane filters are used in sequence for PM determination. They have a diameter of approx. 50 mm and are not more than 100 mm apart.
- The probe shall have a length of 450 mm and an internal diameter of 9.5 mm.
- Deposits are considered as PM and are quantified by washing the sampling line with acetone. The liquid is desiccated at ambient conditions of not more than 30 °C.

European method (draft). The final draft of the European Standard FprEN 16510-1 [4] describes also a PM test method for sampling in diluted flue gas, this method is used for residential solid fuel burning. The main specifications are as follows.

- The partial sampling flow is taken at constant flow from the dilution tunnel with a nozzle orientation of 180° (i. e. with nozzle opening pointing upstream). The nozzle has a diameter of 10 mm.
- The temperature of the diluted flue gas during PM sampling shall be in the range of 25 to 50 °C.
- Filter media is used which is made of glass fibre having a collection efficiency of 99.95 % on 0.3 µm particles.
- Before initial weighing, the filter media shall be dried for 24 h at a temperature which is 35 K higher than the filter holder temperature during sampling (but not more than 180 °C).
- After filter loading and before weighing, the filter media shall be stored in a desiccator for at least 8 hours at ambient temperature.
- In the sampling train, two plane filters are used in sequence for PM determination and are positions not more than 100 mm apart from each other.
- There are some suggestions on the probe specifications itself. The internal diameter should be at approximately 8 mm and should have a length between 300 mm and 600 mm.
- Deposits in the probe are removed by washing the filter holders with acetone once a day. However, the mass of these deposits is not determined and is thus not considered as total PM collected.

A short overview of PM determination performed in the diluted flue gas is given in *Table 3*.

Table 3: Overview of PM determination in the diluted flue gas

Standard	CSA - B415.1-10 (Canada)	AS/NZS 4013 (Australia/ New Zealand)	NS 3058-2 (Norway)	US EPA Method 5G (USA)	prEN 16510-1 (suggested for Europe, alternatively)
Nozzle orientation	90°, vertical to flow	90°, vertical to flow	180°, against gas flow	90°, vertical to flow	180°, against gas flow
Nozzle size	Not stated	Not stated	Not stated	Not stated	10 mm
Isokinetic	Yes	No. Sampling speed set to 0.33m ³ /h	proportionally, 0.015 m ³ /min at mean velocity of 3.33 m/s in tunnel	Yes	Not stated
Filter material	Glass fibre	Glass fibre	Glass fibre	Glass fibre	Glass fibre
Filter retention	99.95 % on 0.3 µm	99.95 % on 0.3 µm	nominal pore diameter of 1.0 µm	99.95 % on 0.3 µm	99.95 % on 0.3 µm
Filters - how many?	a front (primary) filter and rear (backup) filter with distance of 25-100 mm between them	2 filters in series not more than 100 mm apart	2 filters in series not more than 100 mm apart	2 filters in series which are 25-100 mm apart	2 filters in series which are not more than 100 mm apart
Diameter of filter	47 mm	50 mm	approx. 100 mm	minimum of 100 mm	
Filtration temperature	below 32 °C	15-32 °C between both filters	below 35 °C	below 32 °C	filter housing at ambient air temp, but above 20°C
Temperature filter treatment	desiccated at 20±5.6 °C at ambient pressure for at least 24 h	for at least 24 h at ambient laboratory temperature and pressure (no desiccator mentioned)	desiccator for 24 h-36 h at ambient temperature	desiccator for 24 h, alternatively: oven dried at 104 °C for 2-3 h and cooled in desiccator	desiccator for 24 h at 35 K above sampling T, but not more than 180 °C
Rinsing considered?	Yes, weighing the probe assemblies	Yes, probe and filter holders shall be weighed directly or cleaned using acetone	Yes, three times with acetone and brushed	Yes, three times with acetone and brushed	Yes, with acetone

3 Impact on measured PM emission

This chapter deals with different method-based influences on measured particle emission from wood combustion in stoves and boilers. This includes the isokinetic sampling, filtration temperature during PM sampling, the post treatment temperature of the filter media after PM collection, nozzle orientation in the flue gas duct, nozzle size, dust deposition in the sampling probe as well as different dilution strategies of the flue gas.

3.1 Data collection and procedure

Much of the data and findings presented in this chapter are collected from work done within the European EN-PME project which was conducted during March 2012 until December 2014. In addition to this largely unpublished and internal data source, a questionnaire was created and sent out to the IEA Task32-members and their national partners. This questionnaire aimed at providing published or unpublished documentation about experience on influencing factors on measurement accuracy. As a result of this action the response from 7 institutions from 6 countries is regarded and compiled in this report.

It should be noted, that several measurement results shown in the graphs in this chapter sometimes display very high emission levels, which were deliberately caused by improper fuel choices or unfavourable boiler settings. In no way these levels shall be interpreted as typical for practice, nor do they reflect today's state of technology in the regions where these furnaces are applied. This unusual trial management was however necessary to test the effects of different measurement strategies under worst case conditions.

Several of the results concerning the influencing factors in the following chapters were investigated on the test stand at TFZ with a full flow dilution tunnel as shown in Figure 3. PM measurements were conducted with sampling probes and equipment fulfilling the requirements of the German Standard VDI 2066-1. In total up to 4 different sampling ports (TSP1 to TSP4) were used within this investigation. TSP1 to TSP3 were used in the hot, undiluted flue gas while TSP 4 was only used in the diluted flue gas. Not all ports were used for each combustion trial.

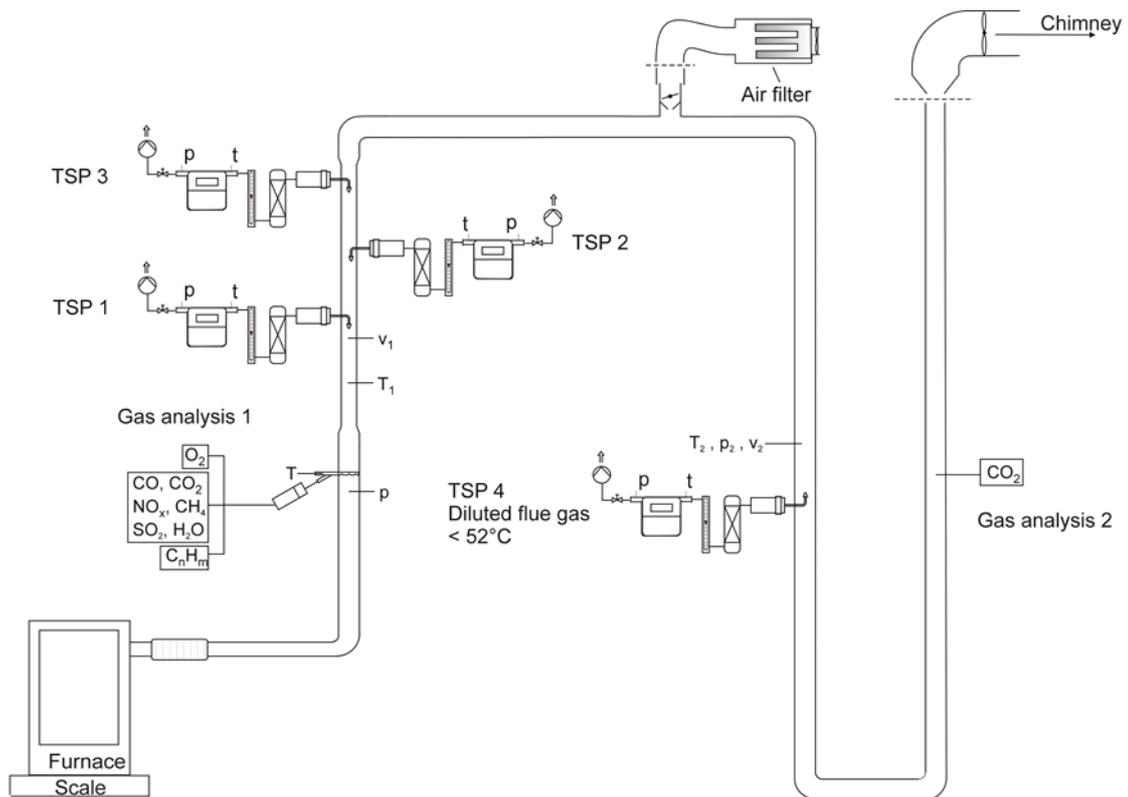


Figure 3: Experimental setup with full flow dilution tunnel as used for the parameter study at TFZ

After PM sampling all filter media (typically quartz fibre plane filter and stuffed cartridge if necessary) were usually thermally treated at 120 °C unless something else is stated. A large variety of sampling probes exist in Europe and some examples are shown in Figure 4. Moreover, furnace type (different firewood stoves and boilers) as well as fuel type (different log wood, wood chips) varied depending on the task and its availability. All presented concentrations refer to 13 vol-% O₂.

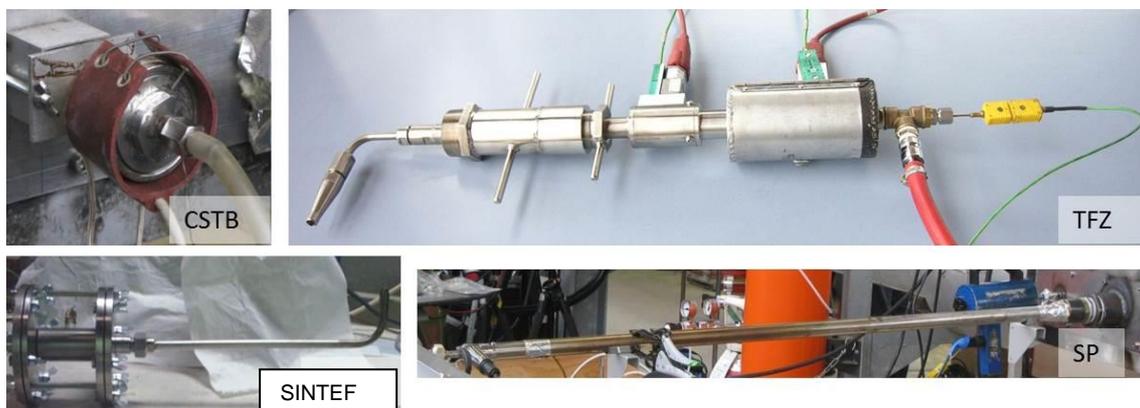


Figure 4: Sampling probes from different institutes such as from CSTB in France, TFZ in Germany, SINTEF in Norway and SP in Sweden. (Source: TFZ)

3.2 Influences assessed

3.2.1 Filter material

Most of the current standards recommend the use of either glass fibre or quartz fibre plane filters. Both filter types were compared in a combustion trial with a firewood stove while sampling in the undiluted flue gas simultaneously. TSP1 was equipped with a quartz plane filter (Munktell MK 360) and TSP2 was equipped with a glass fibre filter (Munktell MG 160), both having a diameter of 45 mm. Stuffed cartridges were not applied. Values between 80 and 300 mg/Nm³ on PM emission were detected. The results are shown in Figure 5, no significant influence of chosen filter media could be observed leading to the conclusion that both filter media are equally suitable for particle sampling in the given case.

The only reported drawback of glass fibre filter is their higher reactivity with acid flue gas components. Another study performed at a firewood stove came to the conclusion that quartz fibre filter detected about 50 % less particle emission compared to the glass fibre filter type [7]. But this investigation was done at different flue gas conditions (not the same batch, no simultaneous measurement) and could therefore be misleading.

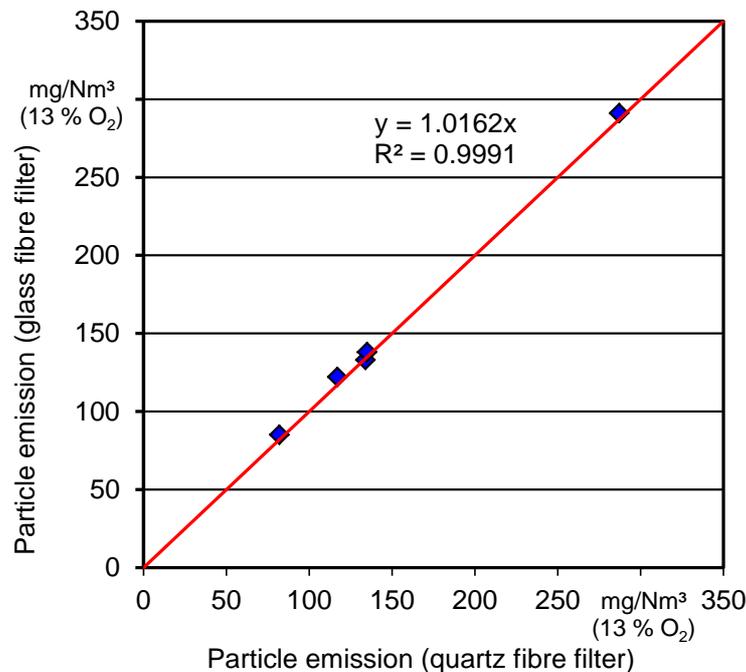


Figure 5: Comparison of two different filter media. Furnace: Austroflamm Chester Xtra, Fuel: beech logs with bark. Source: TFZ

3.2.2 Isokinetic and anisokinetic sampling

Isokinetic sampling is typically recommended for reliable determination of particle emission during biomass combustion. This is of particular relevance for particles larger than 1 µm because they do not behave like a gas and can thus not follow the gas flow easily. For higher sampling velocities than present in the flue gas duct, some of the larger particles will not be sampled whereas at lower sampling velocities a higher share of coarse particles will be collected. Table 4 shows the pathways of smaller and larger particles according to [16].

Table 4: Examples for isokinetic and anisokinetic conditions, according to [16]

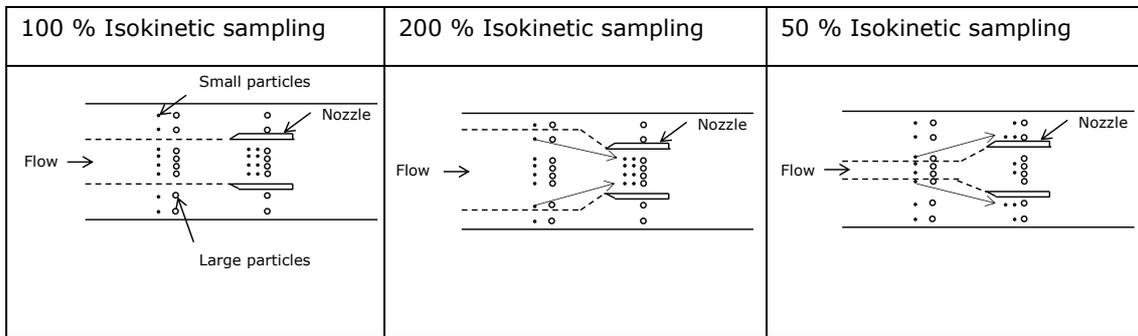


Figure 6 shows the direct effect of sampling velocity on particle concentration as a function of the square root of the Stokes number based on Hinds [21]. The Stokes number can be used since this parameter is directly proportional to particle size (particle size increases with increasing Stokes number). It is also known that if the Stokes number is much smaller than 1 then the particles follow the gas streamlines perfectly [21]. In Figure 6 C_0 is the particle concentration in the flue gas whereas C is the concentration of particles measured at different sampling speeds. Moreover, U_0 is the velocity in the flue gas duct and U is the sampling speed.

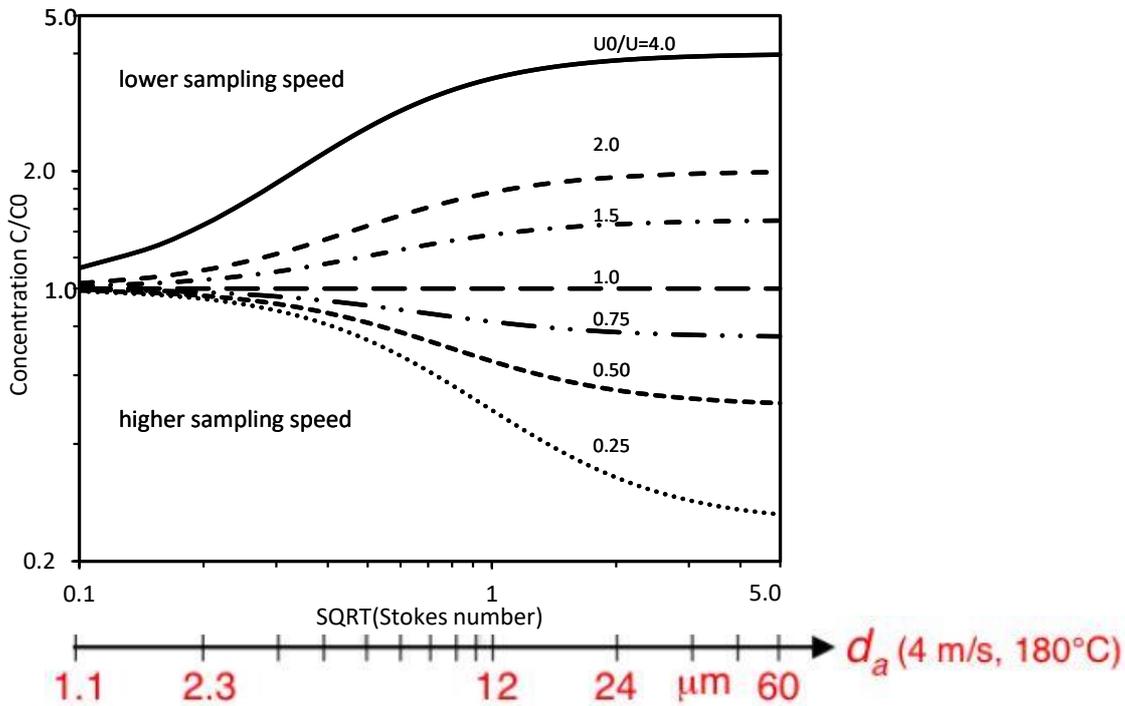


Figure 6: Concentration ratio versus the square root of the Stokes number for different velocity ratio, according to [21]. C_0 – particle concentration in flue gas, C – determined particle concentration, U_0 – velocity of flue gas in the duct, U – sampling velocity. The particle diameter was added according to [13].

The particle concentration will be more affected with increasing particle size indicated by increasing Stokes number, but this should be of minor importance during wood combustion since typically more than 90 % of the particles are smaller than 10 μm as shown in several reports e. g. [17] [22]. Based on this experience it can be concluded that the influence of the sampling speed should not be of

great importance. Further proof was expected to be given in combustion tests, as reported in the following.

The influence of sampling speed was also investigated at different laboratories and the results from two laboratories are shown here. The first campaign using a wood chip boiler was performed at TFZ using three parallel particle measurements with two sampling ports for isokinetic particle sampling (TSP1 and TSP3 for accuracy determination, Figure 3) and one sampling port at TSP2 for isokinetic $\pm 50\%$. A nozzle diameter of 10 mm was selected having a nozzle orientation of 180°. During the combustion of wood chips representing "good" combustion conditions low gaseous emissions (CO between 71 and 80 mg/Nm³, OGC between 1 and 5 mg/Nm³) were released. The diagrams in Figure 7 prove a high accuracy of the particle measurements (TSP1 and TSP3) at "good" combustion conditions. The deposits in the sampling line are not considered in this study. At a reduced sampling speed compared to the flue gas tunnel (i.e. isokinetic - 50 %) an average increase of 7 % in particle emission was detected. For higher sampling velocities indicated by isokinetic - +50 % neither an increase nor a decrease in particle emission was determined for TSP2. From these trials it can be concluded that a high repeatability of particle emission is possible at good combustion conditions. Moreover, it can be recommended that particle sampling should be done either isokinetically or at higher sampling velocity due to the fact that the particles are typically smaller than 10 μm .

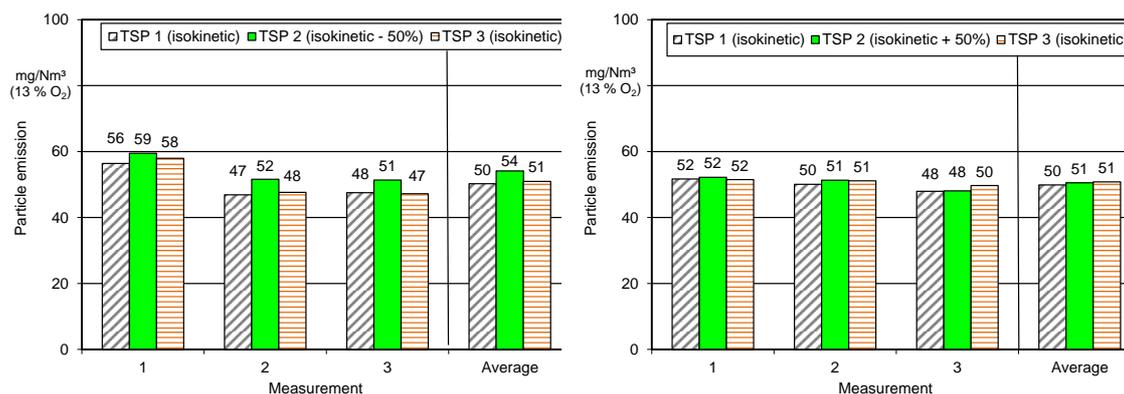


Figure 7: Influence of isokinetic at TSP1 and 3 and isokinetic - 50 % (TSP2, left) and isokinetic + 50 % (TSP2, right) on particle emission during good combustion conditions. Furnace: Guntamatic Powerchip, Fuel: dry spruce wood chips (M = 18 %). Without rinsing. Source: TFZ

At "poor" combustion conditions with wet wood chips (M = 60 %) CO emissions of up to 12,500 mg/Nm³ and OGC emissions of up to 1,900 mg/Nm³ occurred. The parallel measurements at TSP1 and TSP3 showed a lower repeatability of PM emission, Figure 8. At a lower sampling speed (isokinetic - 50 %) an increase in particle emission of 13 % was observed, a similar trend as observed for "good" combustion conditions. At higher sampling speed (isokinetic + 50 %) a slight increase in PM emission was detected, but this was less pronounced than for lower sampling speeds. The deposits in the sampling line are not considered here.

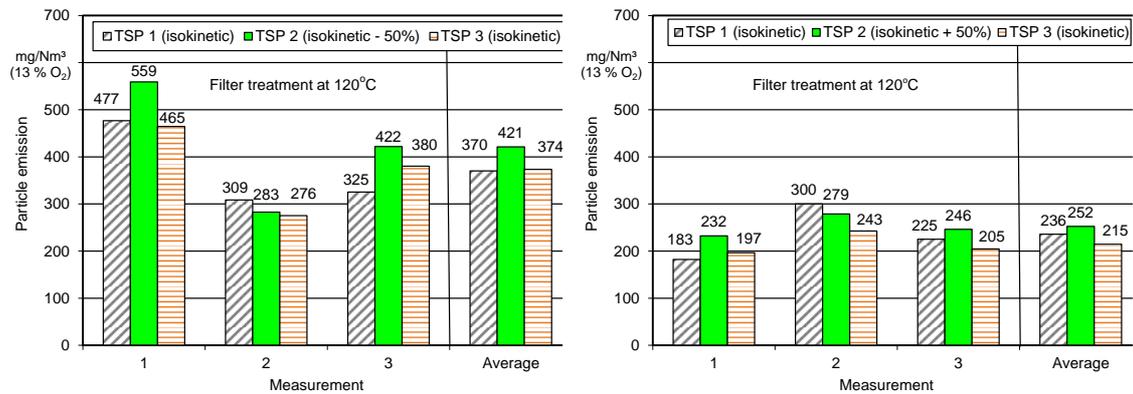


Figure 8: Influence of isokinetic at TSP1 and 3 and isokinetic - 50 % (TSP2, left) and isokinetic + 50 % (TSP2, right) on particle emission during "poor" combustion conditions. Furnace: Guntamatic Powerchip, Fuel: wet spruce wood chips (M = 60 %). Without rinsing. Source: TFZ

From the variation of sampling speed using the same nozzle size it can be concluded that lower sampling speed should be avoided. The same trends were reported in [12].

In contrast to these presented results considerable influence on the isokinetic sampling was reported in [13], see Figure 9. There was an almost 80 % reduction on PM emission if the sampling speed was increased by the factor of 5 compared to the flue gas velocity. This may be due to the fact that a considerable amount of coarse particles larger than 10 μm were released during combustion in the investigated firewood stove. No further information on boundary and combustion conditions was given in the report. It is also not known if the measurements were performed simultaneously.

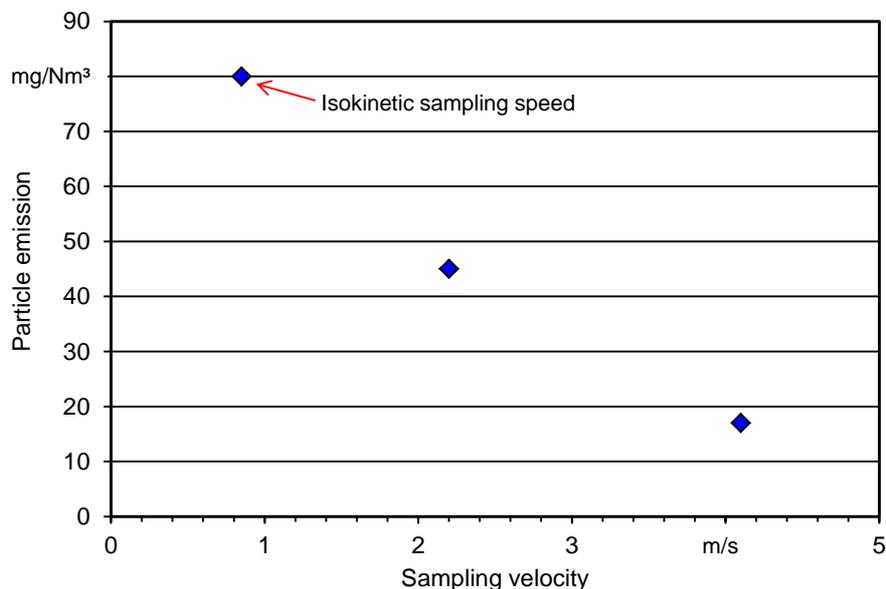


Figure 9: Influence of sampling speed on particle emission using a firewood stove. The lowest sampling velocity represents isokinetic sampling [13]

3.2.3 Nozzle orientation

In cases of isokinetic sampling also the nozzle orientation itself has an influence on the measured particle concentration. A misaligned probe will underestimate the particle concentration as discussed in [21] and presented in Figure 10. Within this figure C_0 is the particle concentration in the flue gas and C is the particle concentration determined at different nozzle orientations. Once again the concentration reduction is presented depending on the Stokes number which is proportional to particle size while depending on flue gas composition, velocities and flue gas temperature. An angle of 90° represents a rectangular position of the nozzle in the flue gas duct. A small misalign of only 15° will only result in a slight reduction of the concentration of particles.

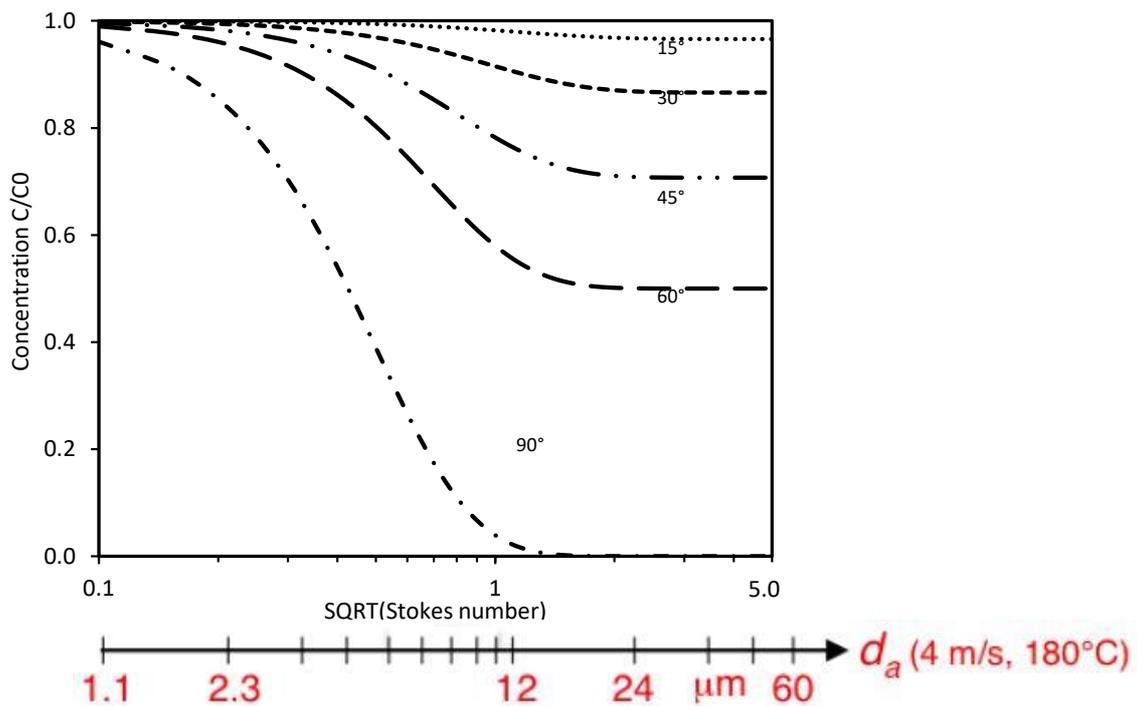


Figure 10: Concentration ratio based on nozzle orientation according to [21], C_0 – particle concentration in flue gas, C – determined particle concentration. The particle diameter was added according to [13].

Data on the influence of nozzle orientation was provided by two different laboratories. At TFZ three different nozzle orientations were compared at “good” combustion conditions using a 10 mm nozzle and isokinetic sampling of flue gas from a wood chip boiler. The nozzle on TSP1 was facing upstream (180° orientation) as it is required in VDI 2066 [3]. At TSP2 the nozzle was in a 90° orientation towards the flue gas flow. And the nozzle of TSP3 was facing downstream (0° orientation). Only plane filters were used and thermally treated at 120°C after dust collection. All TSPs were simultaneously determined and rinsing was considered.

The highest particle concentration was determined with the nozzle facing upstream (180° orientation) with 91 mg/Nm^3 on average. For the other two nozzle orientations lower particle emission were determined, average values of 81 mg/Nm^3 were achieved for the 90° and 0° nozzle orientation, Figure 11. This 10 % PM reduction indicated that both nozzle orientations could lead to the same level of measured particle emission, as the impact on the particles' cut-off sizes (i. e. not collected particle diameters) may be similar.

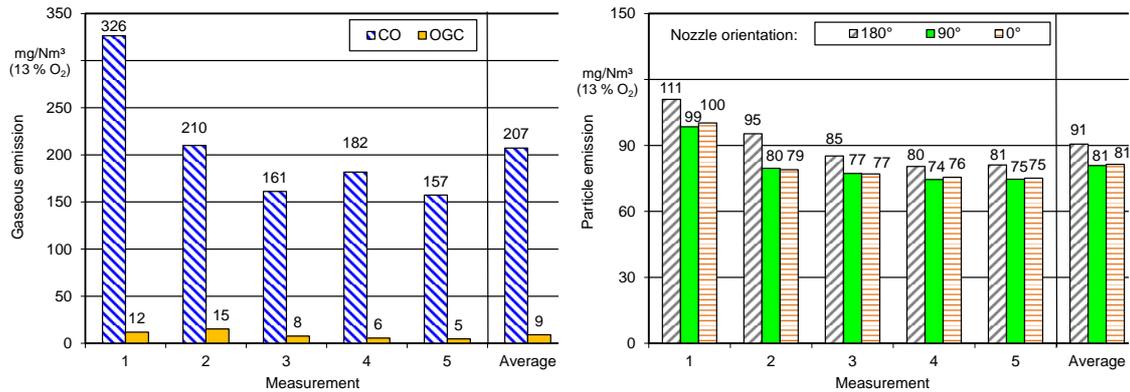


Figure 11: Gaseous emission (left) and particle emission (right) at "good" combustion conditions depending on nozzle orientation. Furnace: Guntamatic Powerchip, Fuel: dry spruce wood chips ($M = 18\%$). Source: TFZ

Further investigations regarding nozzle orientation were performed at the combustion laboratory at FHNW and the data were provided for this report. Parallel measurements were conducted using the Gothe probe (by Paul Gothe GmbH) as well as a probe by Wöhler Technik GmbH (the SM 96 probe). The following nozzle orientations were investigated as shown in Table 5. The Gothe probe is identified by the thicker sampling nozzle.

Table 5: Nozzle orientation for combustion tests, pictures provided by FHNW [15].

Wöhler 180°, Gothe 180°	Gothe 90°, Wöhler 180°	Wöhler 0°, Gothe 180°
		

Three different measurement campaigns were conducted during wood combustion using a firewood stove. The first three measurements were performed in order to prove the suitability of the Gothe probe and Wöhler SM 96 probe for PM measurement using the same nozzle orientation of 180° (pointing against the flue gas flow). The same sampling velocity of 4 m/s was selected while the nozzle size of Gothe was 16 mm and the standard nozzle size of Wöhler is 10.3 mm. For the second set of measurements (measurement number 4 to 7 in Figure 12) the nozzle orientation of the Gothe probe was 90° with a nozzle size of 12 mm. For the last four measurements the Gothe probe was pointing against the flue gas flow (180° orientation) while the nozzle orientation of the Wöhler probe was at 0°. The results are summarized in Figure 12 indicating that the Gothe and Wöhler probe lead to comparable results if the nozzle orientation was at 180°. Only about 70 % of PM emission was detected if the nozzle orientation was set to 90° for the second case study. An even further loss of particle emission was observed when the nozzle of the Wöhler probe was at 0° orientation causing a "loss" of 45 %.

These deviations are clearly more severe than in the TFZ study presented above. The differences may be attributed to the different combustion technologies which had presumably generated different particle size ranges. However, a weak point in the second study may also be seen in the

fact that other influencing factors could not be kept consistent for both devices (i. e. sampling speed, filter media, sampling temperature, pre- and post-filter treatment temperatures) since no information regarding these issues were reported.

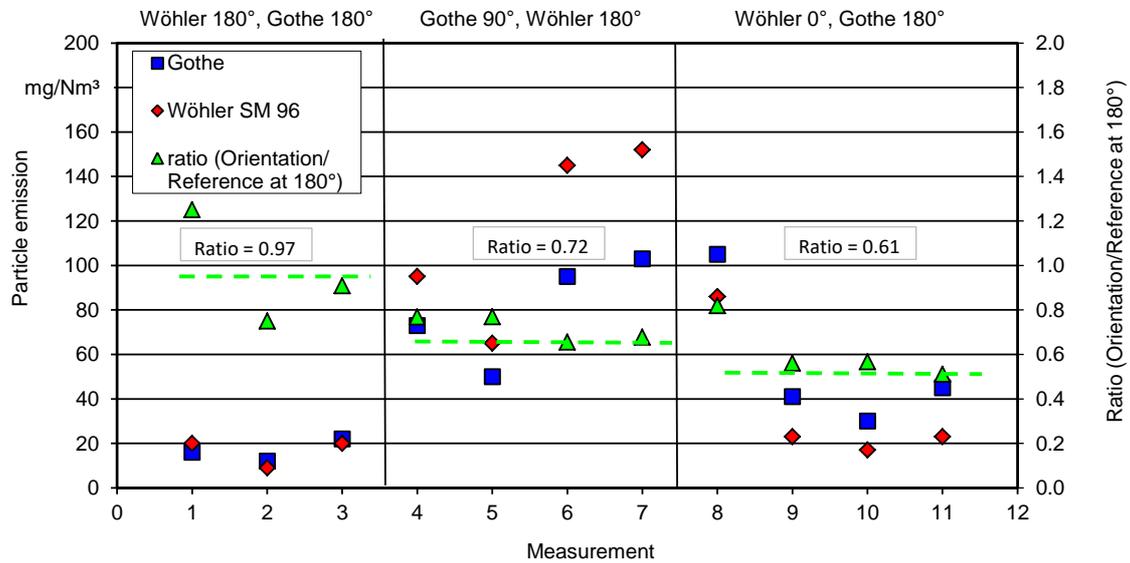


Figure 12: Influence of nozzle orientation investigated by FHNW at a firewood stove. Data provided by FHNW

TSUJI et al [11] investigated the impact of variable operational conditions on the particles' cut-off sizes (i. e. not collected particle diameters) when downstream nozzle orientation (0°) is performed during sampling of particles from pulverized coal combustion and developed a mathematical model. The equation includes the velocity in the flue gas duct (U), velocity at the nozzle (U_0), particle density (ρ_p), nozzle diameter (D_S), cut-off-size (x), the dynamic gas viscosity (μ), particle concentration in the main flow (C_0) and the measured particle concentration (C):

$$\frac{C}{C_0} = \exp\left(-5.09 * \frac{U_0}{U_i} * \frac{\rho_p * U_0 * x^2}{9 * \mu * D_S}\right)$$

The authors assume a cut-off efficiency of 50 % (aspiration efficiency) leading to $C/C_0 = 0.5$. The cut-off-size for the particles can now be calculated as follows:

$$x = \sqrt{\frac{\ln(0.5) * U * 9 * \mu * D_S}{-5,09 * U_0^2 * \rho_p}}$$

Furthermore, the particle density is estimated to be 1000 kg/cm³ and the dynamic viscosity for ambient air (simplified flue gas composition) at around 150 °C is $\mu = 292.65 * 10^{-7}$ Pa s. This simplifies the equation above to

$$x = \sqrt{\frac{\ln(0.5) * U * 9 * 292.65 * 10^{-7} \text{Pa s} * D_S}{-5,09 * U_0^2 * 1000 \text{kg/m}^3}}$$

Now the cut-off-size x can be estimated assuming a nozzle diameter of 12 mm, an average flue gas velocity in the duct of 4 m/s and a sampling velocity at the nozzle inlet of 2 m/s:

$$x = \sqrt{\frac{\ln(0.5) * 2 \text{m/s} * 9 * 292.65 * 10^{-7} \text{Pa s} * 0,012 \text{m}}{-5,09 * (4 \text{m/s})^2 * 1000 \text{kg/m}^3}}$$

All these assumptions in this example predict a cut-off size for particles larger 2.44 μm .

3.2.4 Nozzle size

The influence of nozzle size on particle emission was investigated by DBFZ using a dust tunnel at VSB-TUO in Ostrava, Czech Republic. The nozzle size varied between 4 and 18 mm in diameter. As it can be seen in Figure 13 there is a strong negative influence on the particle concentration with decreasing nozzle size [14]. Therefore, it is recommended to use nozzle diameters that should not be much smaller than 10 mm in diameter in general. It is not clear whether the sampling was done isokinetically, and there is no information regarding the particle size distribution. More research on this issue seems highly recommendable.

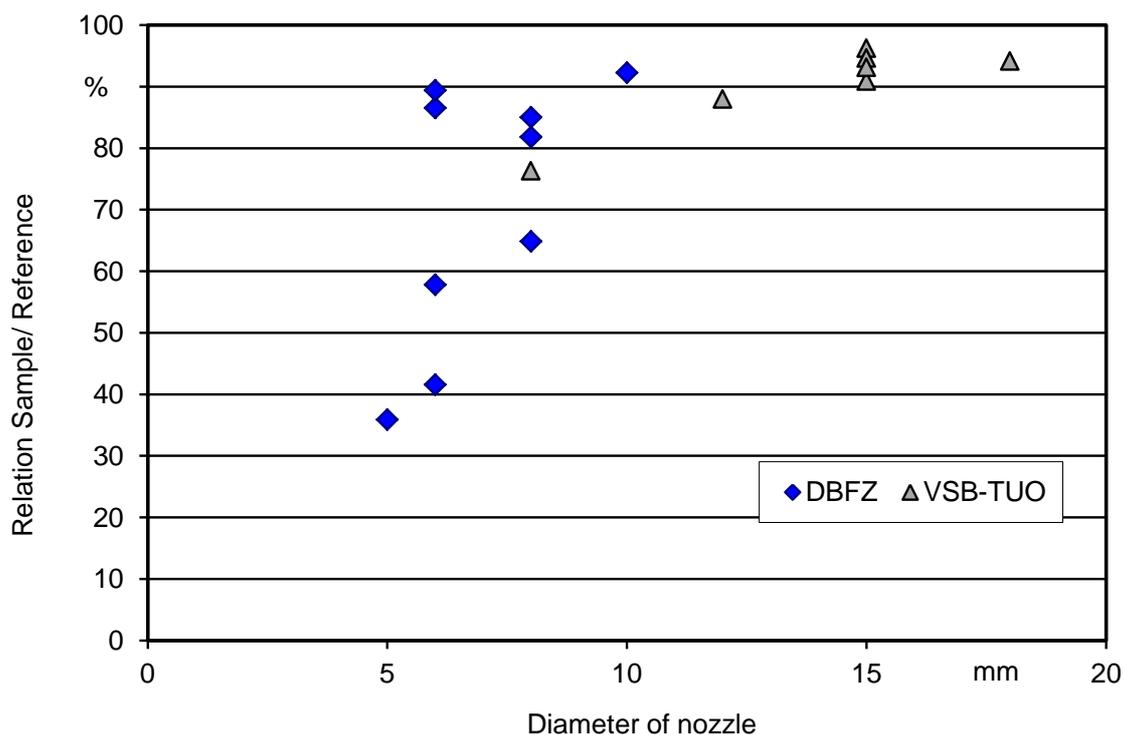


Figure 13: Influence of nozzle size on the deviation of measured particle concentration. Trials performed at the dust tunnel at VSB-TUO in Ostrava using dust collected from an electrostatic precipitator leading to larger particles as released during wood combustion (data provided by DBFZ, measurements performed at VSB-TUO)

3.2.5 Filtration temperature during particle sampling and filter treatment temperature after sampling

Further impact on measured particle emission was expected by the filtration temperature as prevailing over the sampling period. Comparative tests on this impact were performed applying isokinetic sampling using nozzles with 10 mm in diameter pointing upstream to the flue gas flow (180° orientation). The filtration temperature of the first TSP1 was set to 180 °C, while for TSP2 a temperature of 120 °C and at TSP3 a temperature of 70 °C was set. The highest filtration temperature of 180 °C was selected as the reference case as it is required in VDI 2066. The lowest filtration temperature of 70 °C was chosen since this temperature is used by some chimney sweeper devices for field inspection such as the Wöhler SM 500.

During "good" combustion conditions using a wood chip boiler only 64 to 96 mg/Nm³ of CO were released. The right diagram in Figure 14 shows the obtained results on particle emission for the three selected filtration temperatures as well as the influence on filter treatment (120 °C + desiccator and 180 °C + desiccator and direct drying only in desiccator alone) after sampling. Almost

no differences between all particle measurements were detected, the values range from 49 to 51 mg/Nm³ (average of 5 measurements) compared to a sample conditioning in a desiccator alone. This observation is within expectations, as no OGC emission was detected which could have influenced the results by evaporation or condensation. Moreover, an elevated temperature for post treatment did not affect these results from "good" combustion conditions.

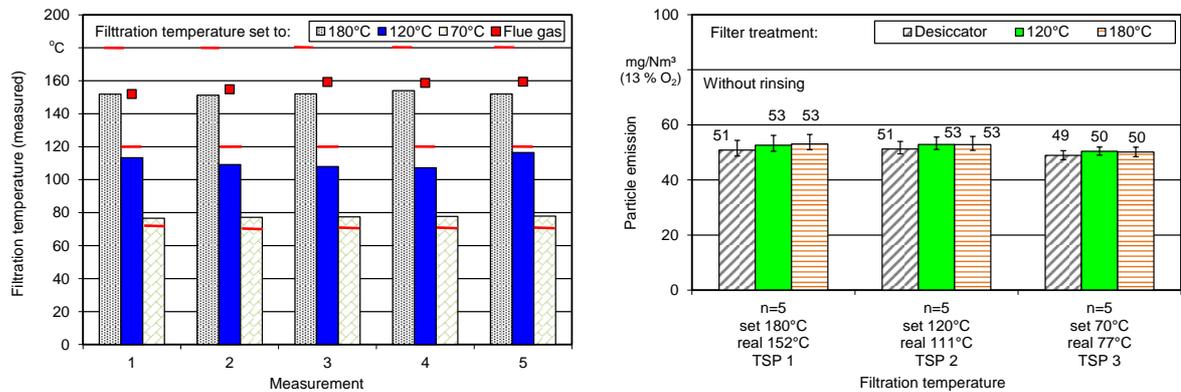


Figure 14: Influence of selected filtration temperature (left) and the thermal treatment after sampling on PM emission (right) at good combustion conditions. Furnace: Guntamatic Powerchip, Fuel: dry spruce wood chips ($M = 17\%$) (Flue gas temperature is given as red marks). Source: TFZ

During "poor" combustion conditions using wet wood chips from spruce having a moisture content of 59 % clearly higher CO and OGC emissions were detected (left diagram in Figure 15). During these five parallel measurements the flue gas temperature dropped down to only 70 °C. Consequently also the measured filtration temperature was drastically reduced despite of the existing probe heating, particularly for TSP1, where filtration was then performed at only 125 °C instead of 180 °C as desired. Obviously it was not possible to maintain the set filtration temperature with the equipment used in this comparison. Technical solutions for maintaining and monitoring the set filtration temperature seem crucial for further development of particle measurement devices, a suitable technical approach is presented in Chapter 4.

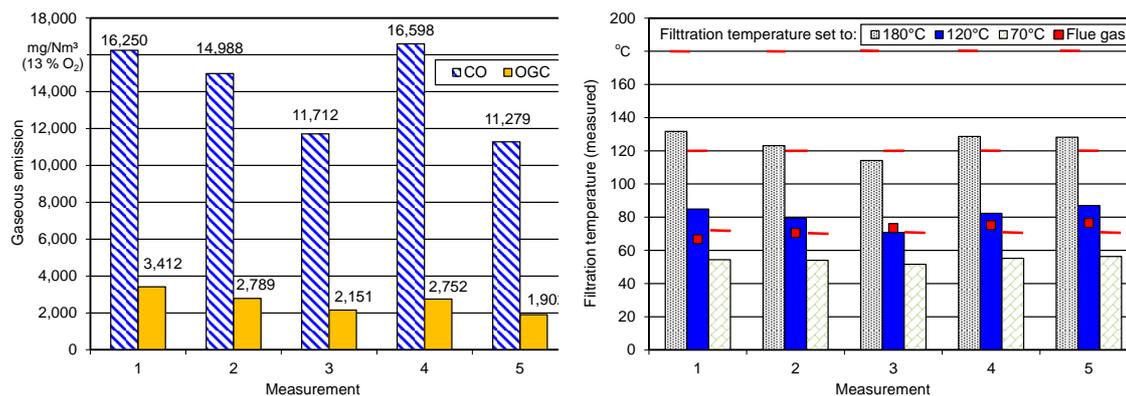


Figure 15: Gaseous emission (left) and filtration temperature (right) at poor combustion conditions applying different filtration temperatures. Furnace: Guntamatic Powerchip, Fuel: wet spruce chips ($M = 59\%$) (Flue gas temperature is given as red marks), Source: TFZ

The results on particle emission measurement using different filtration temperatures at "poor" combustion conditions are summarized in Figure 16. The first diagram (top left) shows the results on particle emission with a set filtration temperature of 180 °C for all five measurements performed at TSP1. Initially each loaded filter was treated only in a desiccator (first column), then at 120 °C followed by a treatment at 180 °C. Between the different temperature levels all plane filters were stored in a desiccator for at least 12 hours and weighted. Only a small influence on thermal treatment was noticed for TSP1 with a mass loss of about 12 %. In contrast to that a clear increase

on particle emission was detected when the filtration temperature was set to 70 °C (TSP3), this increase was 57 % when drying of the filter media was only performed by storage in a desiccator (bottom left). Due to the high OGC content in the flue gas (Figure 15) a further mass loss of 44 % was detected if the filter media was thermally treated at 180 °C compared to the method with only desiccator drying, lower diagram in Figure 16. This observation confirms once more that the mode of post-treatment becomes crucial if the samples are taken at low temperatures and particularly when poor combustion conditions are prevailing.

Moreover, a clear dependency on filtration temperature during sampling is visible, especially if particle emissions are compared without any thermal post-treatment (only desiccator). In Figure 16 an increase from 918 to 2,023 mg/Nm³ on particle emission was detected for the first of 5 measurements. The values vary for the different measurements due to the different flue gas composition as shown in Figure 15.

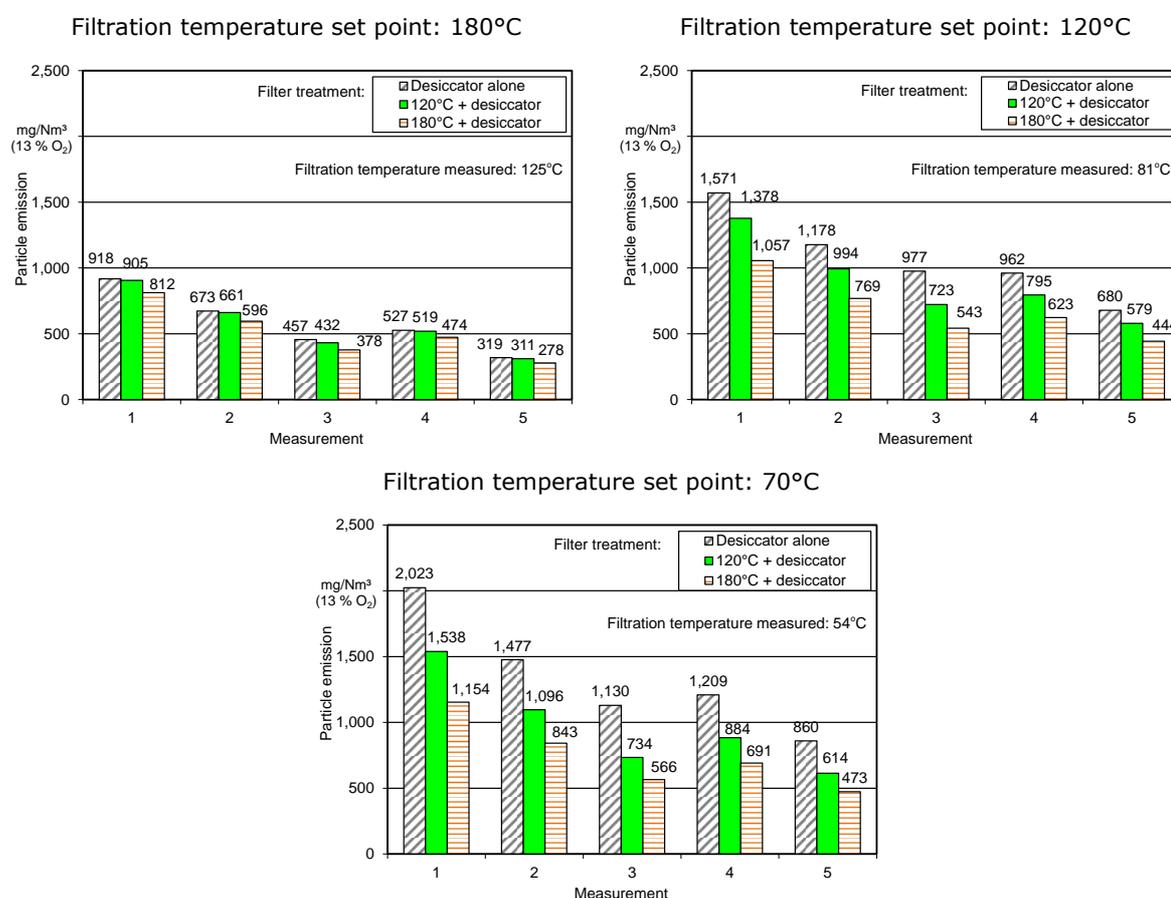


Figure 16: Influence of selected filtration temperature and the chosen thermal post-treatment after sampling on measured PM emission at "poor" combustion conditions. Furnace: Guntamatic Powerchip, Fuel: wet spruce wood chips (M = 59 %). Rinsing not considered. Source: TFZ

The influence on filtration temperature was also investigated by FHNW using two sampling probes with nozzle orientation of 0° and a nozzle size of 10 mm. One of the sampling probes was heated to 80 °C while the other probe was heated to 180 °C. The emission sources were a firewood stove and a pellet boiler. For the firewood stove about 12.4 % lower particle emission were detected if the filtration temperature was set to 180 °C while for the pellet boiler the reduction was only 6.2 %. All filter media were consistently thermally treated at 180 °C after sampling [18]. These results suggest that any increased formation of condensables which are collected at lower filtration temperature on a filter is not fully reversible during post treatment (i.e. drying) at 180 °C.

Special care must be taken for particle sampling from diluted flue gas. This was investigated in a study at TFZ, where diluted temperatures were below 50 °C. The focus was set on the impact of filter treatment after sampling. Two large plane filters (150 mm in diameter) were used in parallel for particle sampling over an entire batch using a firewood stove emitting 4,230 mg/Nm³ CO and 1,063 mg/Nm³ OGC. After sampling the large quartz fibre filter was folded in the middle (to reduce particle losses) and six pieces of the same size were punched out of the filter (see Figure 17) before all filter pieces were weighed after sampling. Then each piece was thermally treated at different temperatures for one hour and conditioned in a desiccator for at least 12 hours before weighing. It was observed that with increasing temperature the particle mass decreased considerably. A mass loss of 50 % was determined for filters treated at 120 °C. Also a 30 % reduction was detected if a temperature of 100 °C was selected. These losses must be attributed to evaporation of condensable matter collected on the filter. Further details from the study can be found in SCHÖN et al. [8].

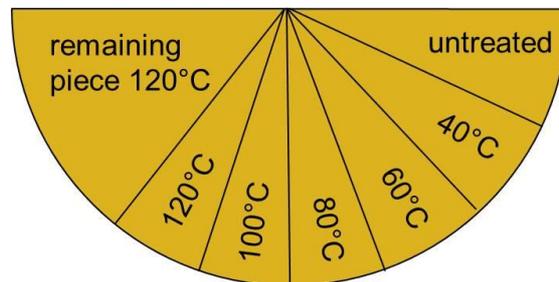


Figure 17: Pieces of the large quartz fibre plane filter with a diameter of 150 mm gained for the investigation on drying temperature impact. Sampling was done from a dilution tunnel. Source: TFZ

The decrease in particle mass by thermal treatment of the filter material was less pronounced if the particles were collected in the undiluted (hot) flue gas, see Figure 18 (red squares). Only a reduction of 10 % was detected if the filter media from the hot flue gas were thermally treated at 120 °C compared to ambient temperature. But almost half of the dust collected in the dilution tunnel was lost due to thermal treatment. More information can be found in SCHÖN et al. [8].

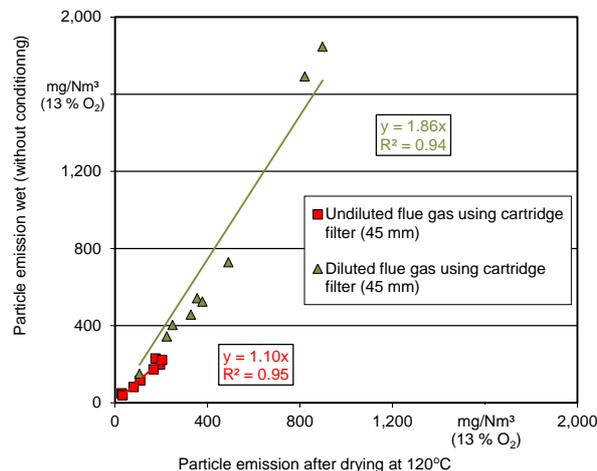


Figure 18: Influence of filter media treatment on particle emission after sampling in undiluted and diluted flue gas using a firewood stove compared to only dried filter. Source: TFZ

3.2.6 Different dilution strategies

It is well known that flue gas dilution contributes to an increase in particle emission especially at high OGC (organic gaseous compounds) concentrations in the flue gas [8][19]. This is mainly caused by partial condensation of none-methane OGCs as already briefly described in Figure 2. If the dilution ratio is varied between 15 to 115 then almost no further increase in PM emission was detected as published by LAMBERG et al. from UEF [24] but the chemical composition may change.

There are several dilution strategies available depending on the parameter of interest. In a case study, two different dilutions strategies were compared. The first method was the full flow dilution with a dilution tunnel as illustrated in Figure 3 (Chapter 3). Particle sampling was performed directly in the dilution tunnel (TSP4) by consideration the dilution ratio determined by an additional CO₂ measurement. Such a setup is typically used in Norway.

The second strategy was the partial flow dilution applying a porous tube diluter (Figure 19) in the undiluted flue gas (TSP2). This is for example a common procedure of researchers in Finland. The filtration temperature for the diluted samples was uniformly set to 50 °C, this was achieved by injecting suitable proportions of filtered ambient air. Apart from the dilution strategy itself the mode of post treatment of the filter media was also investigated. For this the filter media was treated after sampling at three different temperature levels: storage and drying till equilibrium moisture in a desiccator at ambient temperature, thermal treatment at 120 °C as well as at 180 °C. Between the different temperature levels all plane filters were stored in a desiccator for at least 12 hours and weighted. The weight was determined after each of these three treatments.

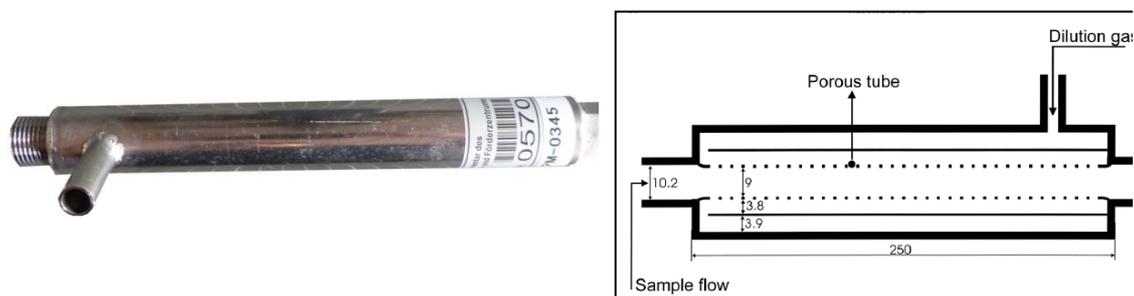


Figure 19: Porous tube diluter for partial flow dilution. Left: Porous tube diluter used at TFZ, Right: schematic drawing taken from MIETTINEN et al. [19].

The effect of flue gas dilution was investigated for two different combustion conditions using a wood chip boiler. "Good" combustion conditions with low OGC content in the flue gas were achieved by burning dry spruce wood chips ($M = 17\%$) at nominal heat output. "Poor" combustion conditions with high OGC content in the flue gas were realized by the combustion of wet spruce wood chips ($M = 60\%$) at partial load. During "good" combustion conditions (94 mg/Nm^3 of CO and 2 mg/Nm^3 of OGC) the sampling temperature for the porous tube as well as for the determination in the dilution tunnel was about $40\text{ }^\circ\text{C}$ while the filtration temperature in the undiluted flue gas was at $110\text{ }^\circ\text{C}$ in average, Figure 20. Regarding particle emissions, only a slight increase of about 8% was detected for full flow dilution while an increase by 13% was observed for partial flow dilution using the porous tube diluter. The rather small increase in PM emission can be explained by low OGC content at "good" combustion conditions, thus the potential for condensation of any gaseous components was low during dilution.

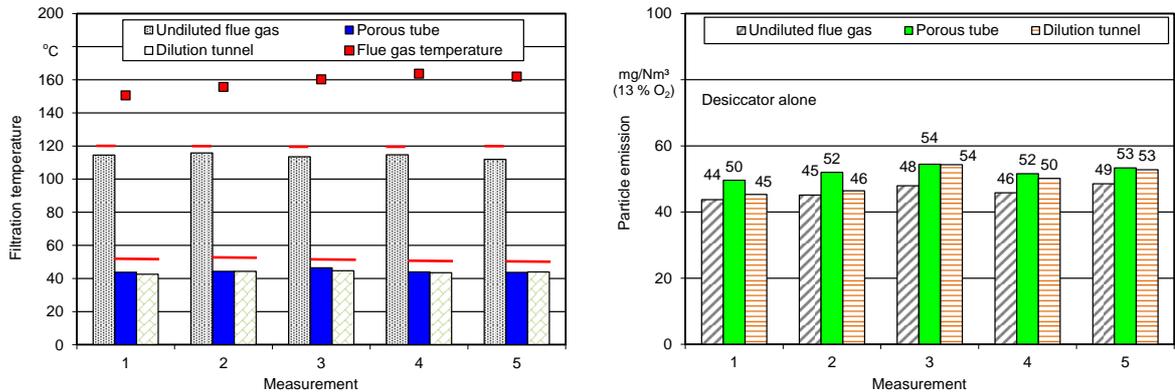


Figure 20: Filtration temperature (left) and particle emission after storing the filter media in a desiccator (right) at "good" combustion conditions. Furnace: Guntamatic Powerchip 30 kW, Fuel: dry spruce wood chips ($M = 17\%$). (Flue gas temperatures are given as red marks). Source: TFZ

Results were largely different at "poor" combustion, where the use of wet wood chips caused high CO (19,339 mg/Nm³ in average) and OGC (4,760 mg/Nm³ in average) emissions, Figure 21 (upper left). A dilution ratio of 2.0 was applied in order to achieve temperatures below 50 °C in the dilution tunnel. The results for different dilution strategies at poor combustion conditions are summarized in Figure 21. The second diagram (upper right) shows particle emissions from all three sampling positions; they were detected without any thermal treatment (only storage in desiccator). A direct effect of flue gas dilution on particle emission is visible by a clear increase compared to hot flue gas. This increase in PM emission is usually more pronounced if the sampling was done in the dilution tunnel at full flow dilution compared to sampling with the porous tube diluter (partial flow dilution). One reason for this deviation could be the extended residence time of the flue gas in the dilution tunnel compared to porous tube dilution.

The two additional diagrams in Figure 21 demonstrate the influence of thermal treatment at different temperatures: 120 °C in the lower left picture and 180 °C in the lower right diagram. With increasing temperature during the post treatment of the filter media a clear decrease in particle emission becomes visible. The mass loss can be explained by additional evaporation of both, water and some easily volatile compounds of OGC leading to a less pronounced particle increase through dilution. Also the differences between both dilution methods decrease with higher post-treatment temperatures: The increase in particle emission determined in the dilution tunnel and after storage only in the desiccator was 63 % while this value decreased down to only 13 % if the filter media was thermally treated at 180 °C and stored in a desiccator after sampling. Therefore, clear treatment specifications are particularly crucial when sampling after flue gas dilution.

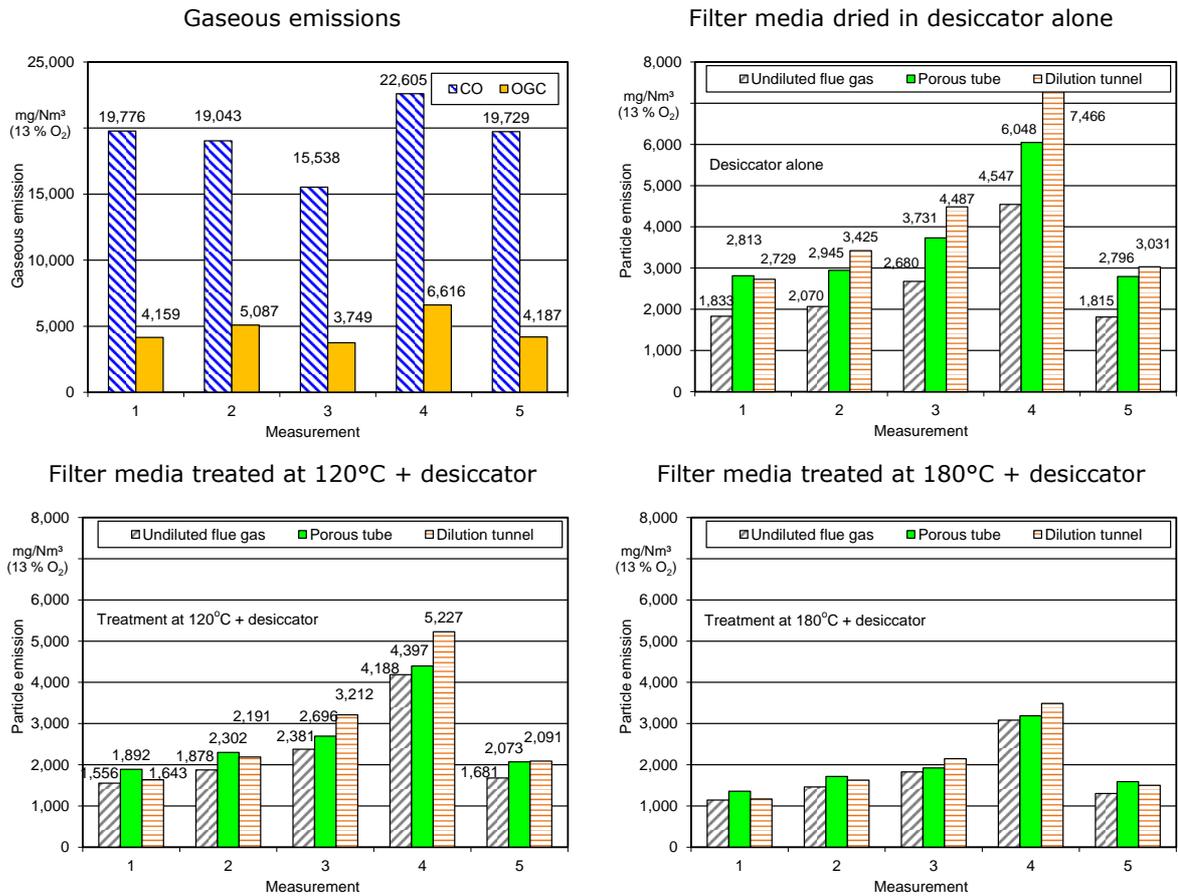


Figure 21: Gaseous emissions (upper left) and particle emission after different treatment of the filter media at "poor" combustion conditions. Furnace: Guntamatic Powerchip, Fuel: wet spruce wood chips ($M = 55\%$). Source: TFZ

Figure 22 shows the increase in particle emission (difference between particle emission determined in the dilution tunnel and particles determined in the hot flue gas) depending on the OGC content in the flue gas for eight different appliances. The dilution ratio varied between 2.2 and 12.6, see [8]. It becomes very evident that with increasing OGC concentration the particle emission increases, too, on a rather linear basis for the chosen experimental setup. In reality the increase is believed to be more pronounced. This is because all filter media in this study had been thermally treated at 120 °C after sampling which is known to have a high effect on the sample mass collected in the dilution tunnel, unlike particles sampled from the hot flue gas. At a lower range of OGC (up to 500 mg/Nm³) no correlation between both parameters was detected (right diagram in Figure 22).

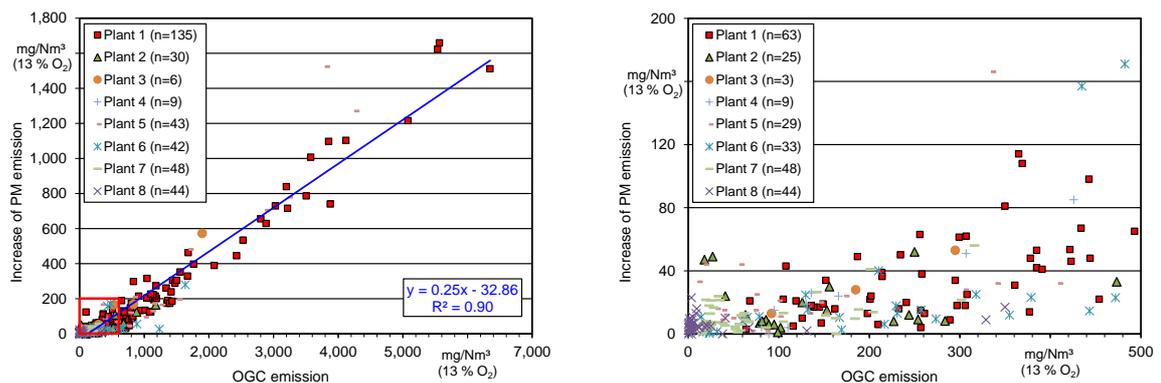


Figure 22: Increase of PM emission over OGC emission using 357 data sets using 8 different combustion appliances. Source: TFZ

3.2.7 Contribution of rinsing to particle emission

Particles absorbed in the sampling tract without arriving at the filter can be regarded as PME. Their contribution can be determined by rinsing and drying of the liquid. This additional - and sometimes disregarded - share of particles was examined by TFZ in the experimental setup shown in Figure 3 (Chapter 3) using TSP1 and TSP4, both at isokinetic sampling speed. For all particle measurements a combination of stuffed quartz wool cartridge and a quartz plane filter was used. Two different firewood stoves, a tiled stove insert and a log wood boiler were applied with different wood fuels.

It can clearly be seen in Figure 23 (left graph) that the use of a plane filter behind the stuffed quartz wool cartridge (if the cartridge is at all required due to expected high dust load) is essential since the particle fraction on the filter varies between 0 and 50 %.

Also the rinsing of the sampling line (done three times with distilled water and acetone) can be of great importance, especially at high OGC concentrations in the undiluted flue gas (e. g. above 2,000 mg/Nm³), where it can account for 10 % to more than 30 % of the total particulate matter. Similar partitioning of the particles in the diluted flue gas is presented in Figure 23, right graph. In contrast to the measurements in the undiluted flue gas the rinsing fraction was lower or usually below 5 % at OGC concentrations above 1,000 mg/Nm³. This can be explained by the fact that most of the condensable particles are not deposited in the sampling line anymore.

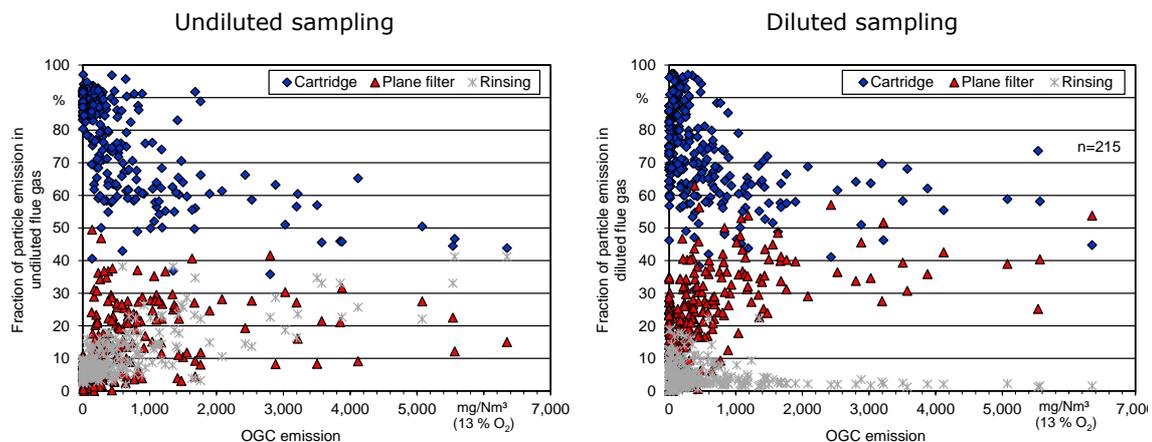


Figure 23: Fraction of particle emission determined in the undiluted (left) and diluted (right) flue gas, depending on OGC concentration. Source: TFZ

3.2.8 Sampling flow rate and deposition in the sampling line

In the previous section it was found out that rinsing of the sampling line which was used in the undiluted flue gas may contribute up to 40 % to the particle emission [8]. Due to low repeatability of the deposition in the sampling line additional tests were conducted while applying different gas velocities in the sampling line. The theory behind this procedure was that at high sampling speed lower deposition rates should occur using the experimental setup shown in Figure 3 (Chapter 3) Wet wood chips were used for creating poor combustion conditions and wheat straw pellets were applied for the generation of mainly of inorganic particles. Three parallel particle measurements in the undiluted flue gas were conducted:

- TSP1: 6 mm nozzle for isokinetic low volume flow sampling (V_{min}),
- TSP2: 9 mm nozzle for isokinetic medium volume flow sampling (V_{medium}) and
- TSP3: 12 mm nozzle for isokinetic high volume flow sampling (V_{max}).

All nozzles faced upstream (180° orientation) and the rinsing of all sampling lines was done after five measurements. Most of the particles were collected in the stuffed cartridge (84 to 96 %). Most important in Figure 24 is the confirmation of the expected influence of sampling speed in the sampling line. While 3 % of particles were deposited in the sampling line at low flow rates during wheat straw combustion only about 1 % of particle emission was collected at higher sampling rates. This behavior is even more pronounced during poor combustion conditions where only 5 % of particles were found in the sampling line at high flow rates compared to the low flow rate with 12 % particle deposition in the sampling line.

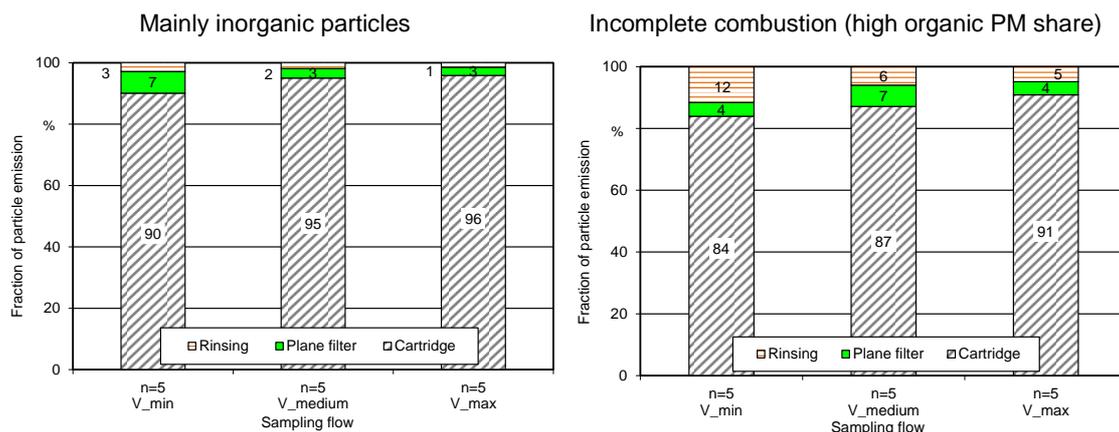


Figure 24: Influence of sampling flow rate on particle deposition in the sampling line for wheat straw combustion (left) and wet spruce wood chip combustion (right) for incomplete combustion conditions. Furnace: Guntamatic Powerchip. Source: TFZ

3.3 Conclusions regarding influencing factors

The presented compilation on influencing factors is fragmentary and sometimes inconsistent. However, as it is the current knowledge basis, the attempt shall be made in the following to draw the main conclusion and recommendations for further optimization of particle emission determination from solid biofuel combustion in room heaters or boilers.

- Usual PM sampling equipment with heated probe and filter holders do not guarantee constant sampling temperatures at given target levels. The set values of the heater should largely be distrusted; filtration temperature monitoring is usually not applied.
- The selection of the filter media has no influence on the determined particle emission as long as the same retention is given unless significant SO₃ concentrations in the flue gas are expected, which leads to an increase in filter weight [3].
- The use of a stuffed quartz wool cartridge as only filter media for PM determination is not recommended and should only be used at higher particle concentration in the flue gas. Always a plane filter should be used and in cases with a stuffed cartridge the plane filter shall be positioned downstream of the cartridge in order to collect any particles that have passed the cartridge or are released as broken quartz fibre particles from the cartridge filter.
- There is indication that any increased formation of condensables which are collected at lower filtration temperature on a filter is not fully reversible during post treatment (i.e. drying) at 180 °C. Consequently a uniform thermal post treatment process at a fixed temperature alone cannot be a suitable measure to harmonize effects from inhomogeneous or inconsistent filtration temperature conditions. This calls for an accurate and proven control of a carefully defined filtration temperature during sampling which needs to be provided by a dedicated probe design.
- It can be recommended to perform particle sampling either isokinetically or at higher sampling speed. Lower sampling speeds may lead to increased particle emission.

- The nozzle orientation influences the results on particle emission. When using a nozzle which faces upstream (i. e. 180° orientation) the highest particle emission measurement is expected compared to the other two possible nozzle orientations (90° and 0°).
- There is some indication, that too low nozzle diameters could systematically underestimate the actual PM concentration. A nozzle size of at least 10 mm in inner diameter is recommended.
- At good combustion conditions with low OGC concentration in the flue gas, higher repeatability of the particle measurements is usually achieved, compared to "poor" combustion conditions.
- At "poor" combustion conditions a clear increase in particle emission is detected if the filtration temperature is reduced.
- Only at low OGC emission no disturbance of measurements is expected by fluctuating filtration temperature during particle sampling or by inconsistent temperatures during thermal treatment of the loaded filter material.
- Flue gas dilution causes an increase in particle emission, especially at high OGC concentrations in the flue gas. The increase in particle emission is slightly less pronounced at partial flow dilution (e. g. using porous tube diluters) compared to full flow dilution (by dilution tunnel). The (thermal) post treatment of the loaded filter media used from a diluted flue gas sampling (i. e. mostly at temperatures below 50 °C) affects the measured PM emission drastically. At lower post treatment temperatures the deviation towards hot flue gas sampling increases.
- Particles absorbed in the sampling tract without arriving at the filter can be regarded as emitted PM. Their consideration by measurement seems necessary, as their share of total particle mass can be in the order of 10 % or higher. Only at low OGC concentrations this share is largely reduced.
- Deposits in the sampling line can clearly be reduced by increasing the sample gas velocity in the sampling probe.

4 Harmonized European method approach – EN-PME method

In the following the main requirements, features and experience on the development of a new European method is compiled. Much of the information presented here is taken from the position paper on “Determination of particulate matter emissions from solid biomass fuel burning appliances and boilers – Proposal for a common European test method” [25]. The main requirements for the new method as well as the experimental setup are included. Selected results from two measurement campaigns are included and discussed in this chapter. This new harmonized method shall be used during type testing and possible product developments as well as for measurements in the field. This method is not developed for research purposes or the determination of emission factors.

4.1 Introduction and requirements

The previous chapters of this report have illustrated the need for a harmonized method in order to be able to compare results with each other. At the same time the new method should fulfil some requirements [9]:

- Investment costs should be low and an easy integration into existing test infrastructure should be possible.
- It is necessary that the new method can be calibrated according to already existing standards.
- The new method should be primarily intended to be used in laboratories as well as for manufacturers for development purposes of their appliances.
- It should be capable of considering particles with diameters down to 10 nm, since they are the most relevant particle sizes for the description of effects on human health.
- The new method should be able to also include the fraction of volatile organic compounds and the emission during transient phases.

Moreover, the new method should be able to cover a rather wide measurement range in order to describe the emission behavior of boilers and firewood stoves properly. Therefore, the suggested new test method consists of a PM measurement in the hot and undiluted flue gas ($PM_{Hot\ Filter}$) combined with a simultaneous OGC determination, while the measurement range for both parameters are defined as:

- $PM_{Hot\ Filter}$: 5 to 200 mg/Nm³ (@13 % O₂),
- OGC: 5 to 1,000 mg/Nm³ (@13 % O₂) and
- Operation range for flue gas temperature: 40 to 400 °C.

4.2 Equipment and boundary conditions

The main goal of this harmonized European method is the reliable determination of PM emission in the undiluted hot flue gas. Since in this approach also OGC shall inseparably be determined along with PM emission, it is important that PM in the hot flue gas and OGC are determined at the same temperatures simultaneously in order to prevent an overestimation or underestimation of organic species. Most of the OGC concentrations are determined using an FID (flame ionization detection) device which is operated at 180 °C. Both values have to be reported separately. Therefore, two sampling lines will be needed. Special care has to be taken regarding the temperature levels in all

sampling lines so that both parameters are determined consistently at a temperature of 180 °C. The nozzle orientation of the PM sampling probe is 90° (rectangular to the gas flow) in order to increase the repeatability of PM measurement by deliberately separating coarse particles. Particle deposits in the sampling line for PM are regarded as emission and will be added to the gravimetric measurement after each run by blowing compressed air into the probe onto a clean conditioned filter which will also be weighed.

The suggested setup for the sampling train for PM determination is shown in Figure 25.

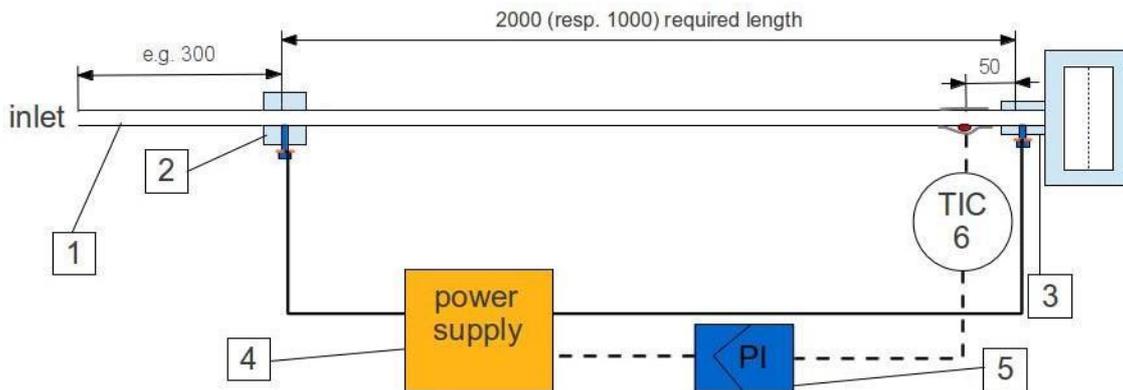


Figure 25: Schematic of the PM sampling probe designed within the EN-PME Test project [9].

The specifications of the PM sampling line are:

- A straight (preferred) or coiled probe heated to 180 °C (± 10 K) for heating and cooling the sample gas with an inner diameter of 7.5 mm and an outer diameter of 8.0 mm
- The probe should be about 2 m long and made of stainless steel (X5CrNi18-10) which is the resistive heating section.
- A filter casing holding a filter, constantly heated to 180 °C ± 10 K
- A sampling volume measurement device equipped with temperature and pressure monitoring, including a drying unit and a pump

The OGC sampling line shall consist of:

- A pre filter set to a temperature of 180 °C (± 10 K)
- A heated line set at temperature slightly above 180 °C to avoid condensation of OGC
- A device to measure water content of the flue gas and a FID running at 180 °C

The orientation of the PM probe was finally chosen to be 90° since this will cause less deposition in the sampling train due to the missing elbow and it will be easier to insert and remove the probe from the flue gas duct. Moreover, no confusion regarding the positioning (against the flow or with the flow direction) of the probe will exist. At the same time coarse particles from the flue gas duct or precipitators are likely not to be detected by the probe. The collection of few of those coarse particles can disturb the repeatability which is expected to be improved by the 90° probe orientation.

4.3 Experience and validation campaigns

During the development stage two measurement campaigns were performed with the new EN-PME-method; in these campaigns the procedure still slightly deviated from the specifications as defined later in the project, while however the EN-PME probe was already in line with the technical requirements defined in Chapter 4.2.

Campaign at INERIS, France. The first measurement campaign was conducted at INERIS in France in February 2014 using a wood chip boiler operating with both, wood pellets and wood chips. The test bench is shown in Figure 26.



Figure 26: Test bench at INERIS/ France with 12 sampling ports. (Source: INERIS)

In total 12 measurement teams (partner 1 was the closest team to the furnace, partner 12 at the last position) participated in the simultaneous determination of both OGC concentration and particle emission using the EN-PME method, here performed at a nozzle orientation of 0° (pointing downstream, which is in conflict with the final definition of nozzle orientation). It has to be noted that the FIDs were operated with different carrier gas (some used pure hydrogen; some used a mixture of hydrogen and helium for a lower cross sensitivity with oxygen in the flue gas). This may cause some slight differences in the OGC concentration in the flue gas since there is a known cross sensitivity for oxygen. For the calibration of the FID not the same gas was used by all partners; some used propane in nitrogen and some partners used propane mixed in nitrogen and 10 % oxygen.

The results for OGC are shown in the left diagram of Figure 27. Fairly good agreement was achieved for this parameter, although the large offset between the highest and the lowest concentration curve indicate that there is still some need for further improvements by quality assurance and instrument adjustment in OGC measurements, too.

PM emissions are shown in the right diagram of Figure 27. At low PM concentrations as achieved in this flue gas, also good repeatability was observed. Some of the results had to be eliminated for various reasons such as false air intake during PM sampling or other technical issues. During the first day of measurement (using wood pellets), low OGC concentrations were detected. Typically during the first measurement of the day the highest OGC emission were released since the wood chip boiler was not yet at stable operation at that time. For the determination of PM emissions the sampling line was rinsed three times at the end of both days (after 5 or 6 measurements) and

fractions of the collected dry deposits were proportionally assigned to each measurement, according to the PM mass collected on each filter. No stuffed cartridges were used.

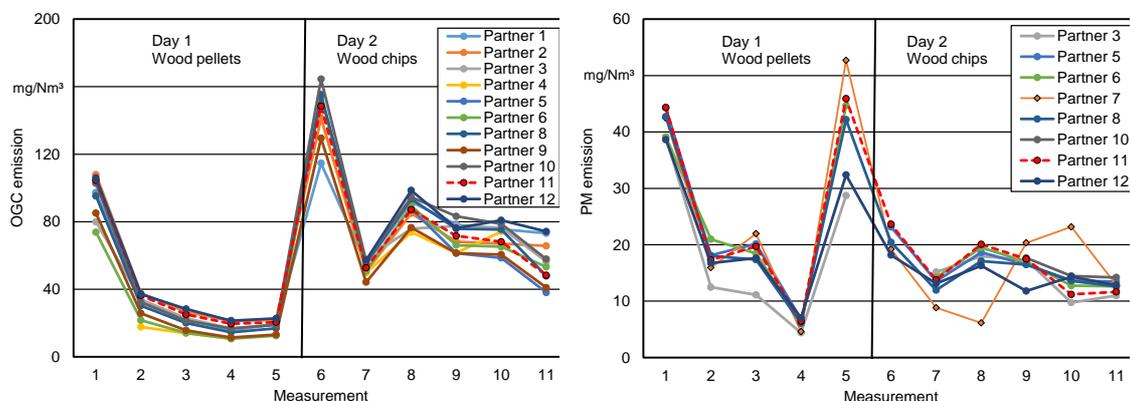


Figure 27: Results of OGC and PM emission determined using the new defined method with 8 to 11 parallel measurements during the campaign at INERIS (Source: DTI, TFZ, unpublished data).

All reliable data regarding PM and OGC emissions were used for the determination of method uncertainty and the values are summarized in Table 6. For OGC the average uncertainty was at 25 % at wood chip combustion and at 42 % during pellet combustion. The average uncertainty for PME varied between 32 % for pellet combustion and 36 % for wood chip combustion. The number of considered values as well as the average value are also included in the following table. These results are unique since no determination of uncertainty was published for PME up to now.

Table 6: Average values, number of considered values and uncertainties of OGC and PM emission during the campaign at INERIS using a wood chip boiler (Source: DTI, unpublished data).

Fuel	No	OGC Measurement			Average uncertainty	PM Measurement			Average uncertainty
		Average [mg/m ³]	Values	Uncertainty [%]		Average [mg/m ³]	Values	Uncertainty [%]	
Day 1 Wood pellets	1	95	9	26.1	42 %	42	7	12.1	32 %
	2	31	10	44.5		17	7	30.2	
	3	21	10	48.5		18	7	38.2	
	4	16	10	51.3		6	7	35.2	
	5	18	9	39.0		41	6	43.6	
Day 2 Wood chips	6	144	7	23.7	25 %	21	4	22.9	36 %
	7	53	10	16.2		13	7	31.8	
	8	87	11	18.9		17	7	57.7	
	9	71	11	21.9		17	8	28.2	
	10	71	11	21.1		14	8	56.7	
	11	56	10	44.9		13	8	15.7	

Campaign at VSB-TUO, Czech Republic. The second measurement campaign was performed at VSB-TUO in Ostrava, Czech Republic, in October 2014 using a firewood stove as emission source, see Figure 28.

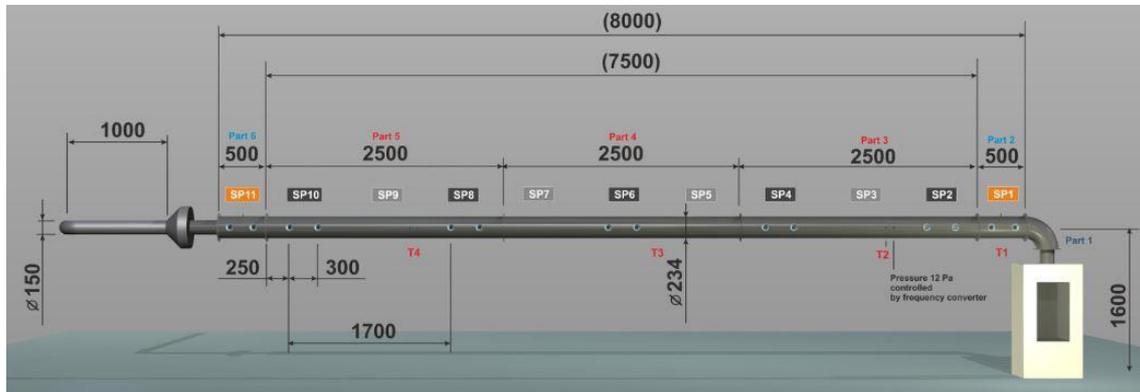


Figure 28: Test bench at VSB-TUO in Ostrava, Czech Republic. (Source: VSB-TUO)

In total 8 measurement teams were present (partner 1 was again located closest one to the emission source); all were using the new PME probe design. The nozzle orientation was again at 0° whereas the inner diameter of the nozzles used by the different partners varied between 5 to 8 mm. Moreover, in some cases the suction speed was varied in two different ranges in order to investigate also the influence of the speed directly at the nozzle. In contrast to the first campaign, OGC was not regarded. The results for PM emission are summarized in Figure 29 where all the values are shown in the left graph and only PM emissions up to 400 mg/Nm^3 in the right graph for better comparison. During measurement number 3 high deviations between the sampling ports were observed. In general most of the determined PM emissions are more or less on a similar level, except for partners 7 and 8. However, deviations are generally high and require further investigation and method tuning.

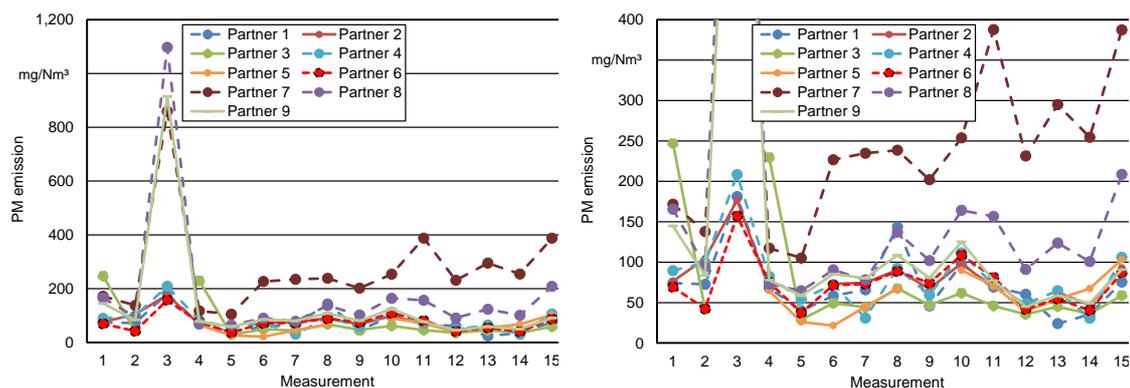


Figure 29: Results on PM emission determined using the new defined method with 9 parallel measurements during the campaign at VSB (Source: DTI, TFZ, unpublished data).

According to the first campaign also the method uncertainty was determined using a firewood stove. The suction velocity at the nozzle inlet was not constant for all partners especially not on the first day (velocity varied between 5 and 11 m/s). The average uncertainty for the first measurement day including five different combustion batches was 91 %, Table 7. On Day 2 and 3 two different ranges of suction speed were selected and chosen by two groups. As it can be seen the average uncertainty was only 38 % at a suction speed between 8-10 m/s while the average uncertainty increased to 135 % at suction speeds between 3.5-5 m/s. The same positive effect of higher suction speed was

proven on Day 3 where the average uncertainty was only 34 % at 7-9 m/s and 167 % at 1.6-2.5 m/s, respectively. It may be concluded that higher suction speeds are beneficial.

Table 7: Average values and uncertainties of TSP during the campaign at VSB using a firewood stove (Source: DTI, unpublished data).

Day Suction speed	Measurement	PME Average [mg/m ³]	Values	Uncertainty [%]	Average uncertainty
Day 1 5-11 m/s	1	117	4	149	91 %
	2	85	9	71	
	3	181	4	23	
	4	98	8	114	
	5	52	8	99	
Day 2 8-10 m/s	6	69	4	21	38 %
	7	61	4	67	
	8	104	4	51	
	9	62	4	39	
	10	104	4	13	
Day 2 3.5-5 m/s	6	95	5	167	135 %
	7	97	5	164	
	8	124	5	114	
	9	108	4	124	
	10	139	5	108	
Day 3 7-9 m/s	11	73	5	16	34 %
	12	49	5	29	
	13	53	5	63	
	14	41	5	39	
	15	90	5	24	
Day 3 1.6-2.5 m/s	11	197	3	177	167 %
	12	119	3	169	
	13	155	3	165	
	14	131	3	172	
	15	218	3	151	

Another issue of interest was the contribution of deposits in the sampling line. Therefore, two different strategies for collecting the deposits were investigated. At the end of one measurement day the sampling line was first blown with pressurized air while collecting the particles on a pre-weighted filter. The second cleaning step of the sampling probe was done by rinsing the probe three times with acetone. It was shown that typically more than 60 % of the deposition in the probe was collected by simply blowing the probe, Figure 30. However, the variation of this share is also quite high. Nevertheless the total share of deposits is typically in the order of 5 % or below (see Chapter 3.2.7), and thus the impact of any deviating procedures is expected to be low, too.

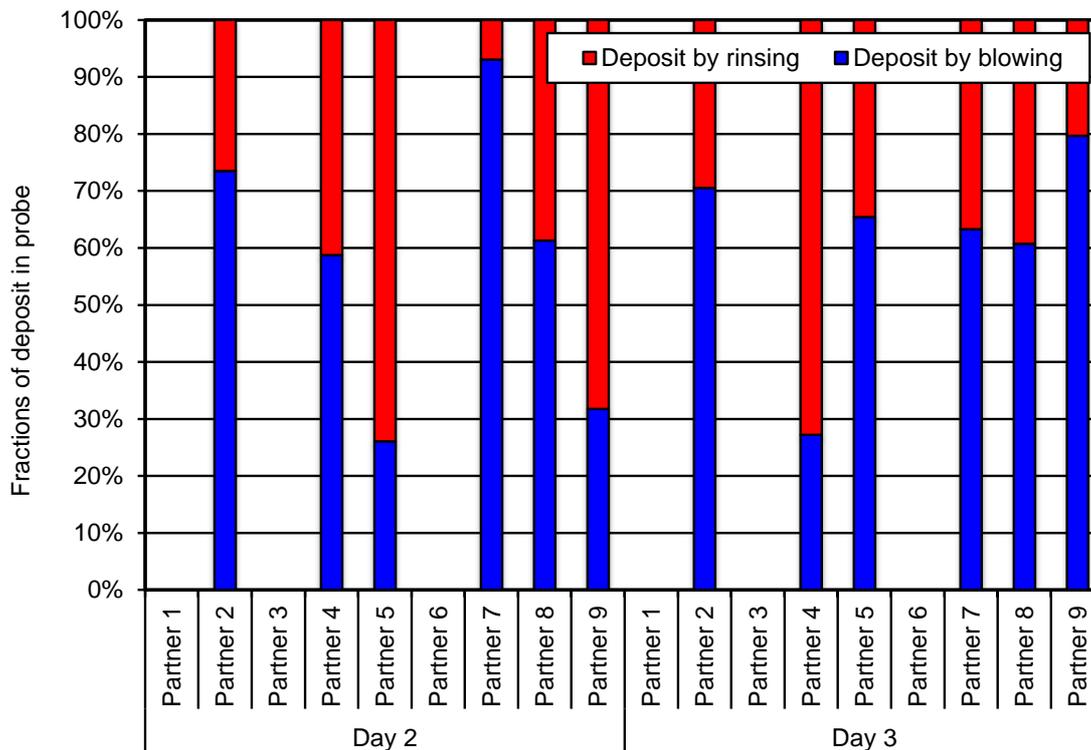


Figure 30: Fractions of deposit in the probe collected first via blowing with pressurized air followed by rinsing the probe three times with acetone at the end of a measurement day (Source: TFZ, DTI, unpublished data)

There are several advantages of removing deposits by blowing. First of all no liquids have to be handled and evaporated. Moreover, the probe can still be hot when blowing the sampling line whereas the probe has to cool down for the rinsing procedure with acetone. These were the main reasons why the blowing of the probe was recommended for the new EN-PME method.

Campaign at TFZ, Germany. After the final proposal of the new EN-PME method was published in [9] an additional measurement campaign was conducted at TFZ. The final method considered a nozzle orientation of 90° using a nozzle with an inner diameter of 7.5 mm and a probe length of 2 m. After each measurement the sampling probe was cleaned with compressed air (6 bar) for 30 seconds while collecting the particles on a clean pre-weighted filter. No rinsing with acetone was performed. The combustion appliance was a wood chip boiler (50 kW) operated at full and partial load. The fuel varied from wood pellets, high quality wood chips to wood chips from short rotation energy crops (SRC). This guaranteed a wide range of particle emission from 20 to about 160 mg/Nm³ with low OGC content (below 17 mg/Nm³) in the flue gas.

The new EN-PME probe was placed between two sampling probes for PM determination in accordance with VDI 2066. The VDI 2066 probes had a nozzle orientation of 180° and they were rinsed three times with a mixture of acetone/isopropanol after each measurement in accordance to VDI 4206. All filter media were thermally treated at 180 °C after sampling. Each sampling lasted for 15 minutes. The average values between both VDI 2066 sampling ports were used as reference value for the EN-PME method.

The results are shown in Figure 31. In general a rather good agreement between both methods can be confirmed, especially for wood chips. The PM emission determined with the EN-PME method was about 7 % below the reference method which may be attributed to the different nozzle orientation

and different procedure for probe cleaning. Larger deviations occurred for pure wood pellets. The contribution of deposits in the sampling line of the EN-PME method collected by blowing was as low as 5 % in average while the contribution of deposits collected through rinsing of the VDI 2066 probe was as high as 15 % in average.

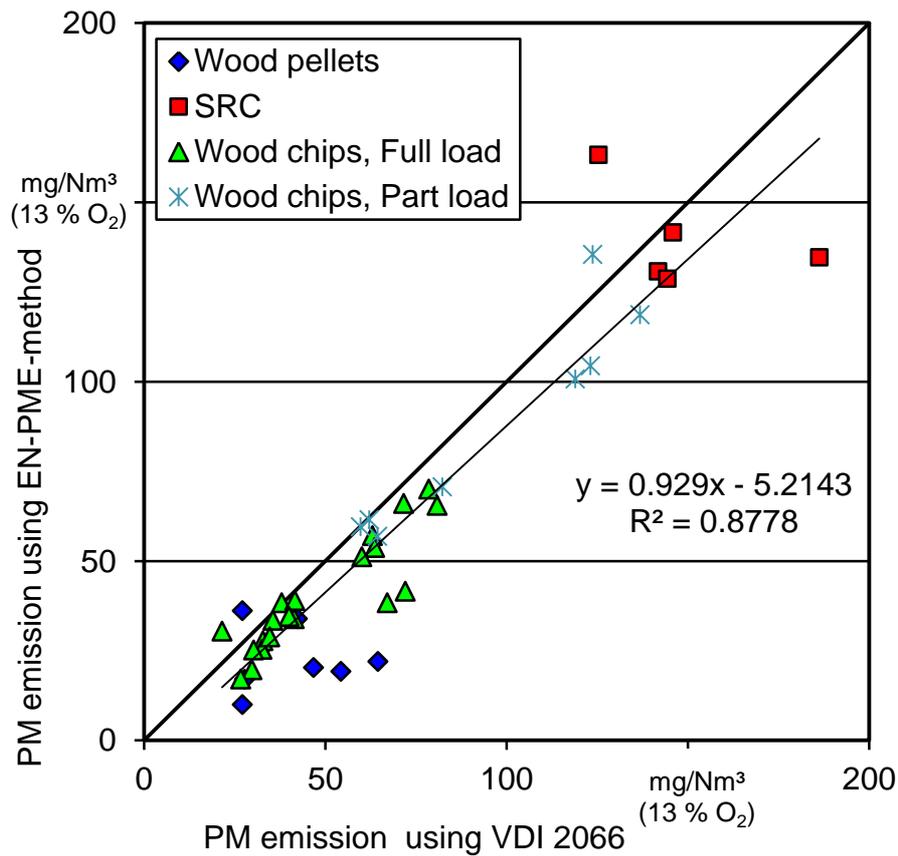


Figure 31: Comparison of PM emission determined by the reference method following VDI 2066 and the new EN-PME method. Furnace: Wood chip boiler. Fuel: Different fuel assortments. (Source: TFZ)

More measurements should be conducted especially during log wood combustion with rather high OGC emission.

5 Summary and conclusions

This report draws attention to the diversity of gravimetric PM emission measurement methods and to the need for method development and international harmonization. An inventory of existing standards and their characteristics is prepared, followed by a compilation of laboratory experience concerning method-based factors which influence the measured particle emission (PME). Finally, a recently discussed approach for a modified international method is presented, the so-called "EN-PME method".

From the presented review of existing standards for particle emission determination (Chapter 2) it becomes obvious that direct comparison of results which were created with reference to either of the cited methods are not compatible. Furthermore, the standards allow a high diversity of measurement devices and leave much room for interpretation and adaptation of procedures. And many of various possible impacts which may affect the results are yet unspecified.

Therefore a compilation of existing and accessible knowledge on quantifiable influences of method variations was prepared, including filter material, isokinetic flue gas sampling, nozzle size and orientation, filtration temperature during PM sampling, filter treatment temperature as well as rinsing of the sampling line and its contribution to PM. Briefly compiled, the main conclusions are as follows.

- The selection of the filter media seems to have no influence on the determined particle emission in wood combustion.
- There is some indication, that too low nozzle diameters may systematically underestimate the actual PM concentration. A nozzle size of at least 10 mm in inner diameter seems desirable.
- It is crucial to maintain a constant filtration temperature during PM sampling to obtain comparable results. A uniform thermal post-treatment process at a fixed temperature alone is believed not to compensate differences from inhomogeneous or inconsistent filtration temperatures throughout the sampling duration.
- This calls for an accurate and proven control of a carefully defined and fixed filtration temperature which needs to be realized by a dedicated probe design.
- Today's heated probes and filter holders do not automatically guarantee constant sampling temperatures at given target levels.
- With the heated filter method particles from incomplete combustion will partly be disregarded during sampling as condensation is largely avoided. However, the potential formation of such particles could be evaluated by parallel measurement of total organic gaseous carbon (OGC).
- If both parameters, PME and OGC, are evaluated for assessing the potential for aerosol formation, it shall be ensured that both measurements are also performed at the same temperature. This is to avoid that organic species in the flue gas are determined twice, once as gaseous substances via FID and a second time as condensed particles collected on the PM filter. Both parameters have to be determined at 180 °C.
- Isokinetic flue gas sampling may be required if coarse particles shall always be collected representatively (at a nozzle orientation of 180°).
- The nozzle orientation influences the PM emission and any misalignment will cause a cut-off of coarser particles.

- Deposits in the probe should be considered as PME, either by rinsing or at least by blowing out pneumatically over a clean filter; this should always be stated in the measurement report.
- Deposits in the sampling duct are reduced if sample gas velocity in the probe is increased.
- Higher repeatability of PM measurement results is usually achieved at good combustion conditions with low OGC content in the flue gas compared to poor combustion conditions.
- A nozzle orientation of 90° would simplify the insertion of the sampling probe into the flue gas duct and would reduce the risk of inaccurate positioning of the nozzle.
- However, at a 90° nozzle orientation a certain and not known share of coarser particles would not be considered as PM emission. A distinct cut-off size cannot be identified, this would depend on several parameters such as velocities and flue gas properties.
- Flue gas dilution before PM sampling introduces a large diversity of new measurement errors compared to undiluted PM sampling via heated filters. In a harmonized method for wood boilers or stoves, dilution has to be avoided especially during type testing. Flue gas dilution is, however, a useful and required treatment in scientific studies where particle composition, size distribution of particles and emission factors are determined.

From the presented review of existing standards and the conclusions derived from the impact study the need for method harmonization becomes obvious. An attempt to implement many of the above findings by defining such a new method was made in the EN-PME project which is briefly described in Chapter 4. This method is basically demanding the use of a new probe for a heated filter method with a controlled and constant temperature of 180 °C at the filter, a simplified 90° orientation of the nozzle in the flue gas duct, a fixed inner nozzle diameter of only 7.5 mm to guarantee high sampling gas velocities and a quantification of PM deposit in the probe by clean purge air rinsing which is then conducted over a clean filter after each measurement. Furthermore, OGC shall inseparably always be determined along with PM emission. This requirement follows the hypothesis that OGC is a suitable parameter to characterize the potential formation of aerosol particles from incomplete combustion. Thus, a parallel OGC measurement becomes an integral and inseparable part of the EN-PME method, OGC shall be analyzed at the same sampling temperature of 180 °C as applied during PM filtration.

Discussions concerning the future use of this EN-PME method are ongoing, for example further validation work is being carried out during the coming years within the European standardization group of CEN TS 295 (WG 5). Whether the EN-PME method can serve as a blueprint for international harmonization will depend on a number of requirements and on compromises which still need to be agreed on:

- *Nozzle orientation and cut-off diameters.* The suggested 90° nozzle orientation requires a shift of paradigm as a small but non-quantified share of coarse particles will thus deliberately be excluded from sampling. This specification may fit to the assumption, that such particles are usually considered less harmful from the perspective of human health impact. Furthermore, the total error by their exclusion is regarded low for many wood burning appliances, as they either discharge only low quantities of coarse particles or they could easily be equipped with cyclones for coarse particle separation. But for general agreement it seems recommended that trustful information about the maximum expected range of excluded aerodynamic particle diameters will be provided.

- *Fixed nozzle diameter.* In view of the indication that larger nozzle diameters are desirable (Chapter 3.2.4) the definition of a small nozzle with only 7.5 mm inner diameter as a standard needs to be explained or still calls for validation.
- *Compact design.* The achievement of a constant filtration temperature at 180 °C requires a relatively long heating and cooling line upstream of the filter (e.g. 2 m as realized in the previous prototypes). For easy probe handling a compact design e.g. coiled probe is currently tested at CATSE.
- *General proof of accuracy.* In view of the quite variable results from the comparative testing of the EN-PME method (see Chapter 4.3) it seems desirable to determine the actual repeatability and reproducibility limits in further test campaign. However, the difficulty to compare and evaluate such results will remain, because reference data hardly exist for today's PM determination methods. No other method to measure PME from small scale biomass combustion was ever tested simultaneously by different measurement teams to calculate the expanded uncertainty. Therefore, the EN-PME method is the best investigated method ever developed for PME from small scale biomass combustion.

Finally it may be concluded that efforts for harmonization and comprehensive specification of methods for determining PM emission need to be strengthened. The EN-PME method can serve as useful basis for these efforts. However, this approach may not be reaching out far enough. This is because the equipment after the newly designed heated sampling line will probably require some harmonisation, too (design of filter casing, filter diameters, pump, etc.). But perhaps even more important is the overall laboratory infrastructure and the largely self-defined handling procedures. Comprehensive rules for filter pre-treatment, post sampling treatment (e.g. heating, cooling, storage, filter transportation) and the application of general quality assurance tools may in the future be required, too. This becomes particularly evident when regarding simultaneously generated PM measurement results, where sometimes disturbingly inconsistent measurement results and outliers are reported. Some examples are shown in this report. It is likely that results from other similar campaigns display similar variations and that there is good reason for not disclosing them.

In general, the desired method harmonisation appears to be an extremely ambitious task. Work has just begun.

6 Literature

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