

Particulate Emissions from Biomass Combustion in IEA Countries

Survey on Measurements and Emission Factors

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On behalf of

International Energy Agency (IEA) Bioenergy Task 32

Swiss Federal Office of Energy (SFOE)

Download www.ieabcc.nl or www.verenum.ch

Zürich, January 2008

ISBN 3-908705-18-5

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1 Abstract

Biomass combustion, especially in small-scale applications, is related to high emissions of particulate matter (PM) smaller than 10 microns (PM_{10}). Since PM_{10} is regarded as a major indicator for the health relevance of ambient air pollution, a further propagation of biomass combustion is hindered by the disadvantage of high PM emissions. The International Energy Agency (IEA) Bioenergy Task 32 on Biomass Combustion and Cofiring is promoting the utilization of clean biomass combustion applications to replace fossil fuels and to reduce CO_2 emissions. Hence IEA assists the development and implementation of technically and economically feasible measures for PM reduction. As a basis to set priorities for the implementation of measures and as a guideline for future regulations, emission factors from different types of combustion devices under different operation modes are needed. The present study gives a survey on emission factors as reported from the member countries of the IEA Task 32. To collect information, a detailed questionnaire was sent to all member countries. A total of 17 institutions from seven countries, i.e., Austria, Denmark, Germany, Norway, The Netherlands, Sweden, and Switzerland, participated in the survey. Valuable data are available for residential wood combustion, whereas data from automatic combustion plants are strongly related to particle removal equipment and national or local emission limits. Hence the results refer mainly to residential wood combustion and show that huge ranges are found for manual wood combustion devices. For existing stoves and boilers, ideal operation is regarded as a major target to reduce PM emissions. Furthermore, the method of ignition is important for the PM emissions of wood stoves and boilers. For typical wood stoves, ignition from the top of the batch of wood logs instead of ignition from the bottom can often avoid visible smoke during start-up and reduce the total PM emissions by more than 50%. For log wood boilers, beside optimised ignition and start-up, the implementation of a heat storage tank is essential, as thanks to a heat storage, part-load operation related to high PM emissions can be avoided. With respect to the measurement of PM emissions, the mass on solid particles in the hot flue gas (as collected on filters) and the additional mass of condensables need to be distinguished. Under poor combustion conditions, the mass of condensables can exceed the mass of solid particles and hence should be considered in future immission inventories.

Keywords: Emission factor, particle emissions, condensables, wood combustion.

2 Introduction

2.1 Motivation

Biomass combustion is an important source of inhalable particulate matter smaller 10 microns (PM_{10}) in the ambient air. Since PM_{10} is regarded as one of the most relevant parameters in air pollution [Dockery et al. 1993, Donaldson et al. 2002], the PM emissions from biomass combustion can hinder the further propagation of bioenergy. To overcome this disadvantage, detailed information on particles from different combustion applications are needed. Based on these data, the most significant particle sources among biomass combustion can be identified and measures for PM reduction can be deduced. Consequently activities on the characterisation of particle emissions from biomass combustion have been performed in many IEA countries in the past years or are currently ongoing.

2.2 Objectives

The objectives of the present study is to review available data on emission factors of particulate emissions from biomass combustion and measurement techniques applied to characterise particle emissions from biomass combustion. Priority is given to wood fuels used in residential wood combustion and in district heating plants. To enable a comparison of different data, the sampling and measurement techniques shall be documented and differences due to different sampling or analysis shall be discussed. Furthermore, the influence of combustion type, fuel parameters and different operation conditions on PM emissions shall be identified.

2.3 Work programme

The main work method was to collect emission data from research institutes and universities and to review official national emission factors. Furthermore, information on measurement methods was collected. For this purpose, a detailed questionnaire on particles was compiled and sent to IEA appointed experts. Beside this, certain data available from literature were also considered in the survey. Relating to emission factors the questionnaire comprehends residential wood burning as well as industrial wood combustion. The residential category consists of fireplaces, manual stoves, manual boilers and pellet combustion, each case with subcategories oriented on technology and wood fuel (log wood, pellets). The industrial sector includes automatic boilers with categories from < 70 kW to > 10 MW and subcategories related to technology. For the emission inventory data a range of values were requested for best results at ideal operation, typical results at practical operation and worst results at very bad handling. Values were also differentiated between measurements with and without start phase emissions and measurements for solid particles (indicated as SP), solid particles plus condensables found in impinger bottles (SPC), and total particles collected in a dilution tunnel (DT).

3 Particulate matter in the ambient air

3.1 Characteristics of particulate matter (PM)

Particulate matter (PM) describes the sum of airborne solid particles and droplets. PM, also known as particle pollution, is a complex mixture of airborne particles and liquid droplets composed of acids (such as nitrates and sulfates), ammonium, water, black (or “elemental”) carbon, organic chemicals, metals, and soil (crustal) material. The particle size is the most important parameter for the characterisation of particle behaviour. PM₁₀ summarizes all particles and droplets with an aerodynamic diameter smaller than 10 micrometer (microns). EPA groups particle pollution into two categories [EPA 2008]:

- "Coarse particles" (PM_{10-2.5}) such as those found near roadways and dusty industries range in diameter from 2.5 to 10 micrometers (or microns). The existing “coarse” particle standard (known as PM₁₀) includes all particles less than 10 microns in size¹. EPA has proposed replacing this standard with one that includes only particles between 10 and 2.5 microns in size (i.e., PM_{10-2.5}).
- "Fine particles" (or PM_{2.5}) such as those found in smoke and haze have diameters less than 2.5 microns. PM_{2.5} is referred to as “primary” if it is directly emitted into the air as solid or liquid particles, and is called “secondary” if it is formed by chemical reactions of gases in the atmosphere.

Beside coarse and fine particles, ultrafine particles smaller than 0.1 microns are distinguished (e.g. [Hinds 1999]). The size and density affects the retention period and travel distances in the atmosphere. Coarse particles tend to settle to the ground by gravity within hours, while fine particles can remain in the atmosphere for several weeks. Furthermore, limit values for both, particle emissions as well as PM immissions are indicated as mass concentrations. This does not respect the large surface of fine particles which can act as potential carrier for toxic substances. Hence beside mass concentrations, additional parameters are relevant for the potential impact of particles on environment and human health. In particular the particle size, the particle shape, the morphology, and the chemical composition are important parameters which need to be respected in addition to the mass. For typical conditions, approximately 90% of PM consists of fine and ultrafine particles [UBA 2005]. Since PM indicate only mass concentrations, there are considerations for further parameters such as particle number and toxicity which might be respected for future limit values.

Particulate matter in the ambient air is a mixture of directly emitted primary aerosols and secondary aerosols formed in the atmosphere. PM is partially of natural origin, while anthropogenic emissions lead to additional PM in the ambient caused by primary and secondary aerosols. Coarse particles from primary aerosols originate mainly from mechanical processes (construction activities, road dust, re-suspension, wind etc.) whereas fine particles are particularly produced through combustion [WHO 2006]. Main sources of primary particulate matter are Diesel engines and biomass combustion. Secondary aerosols are formed in the atmosphere through conversion of gaseous precursors

¹ In German, the expression „Feinstaub“ („fine particles“) is used to describe PM₁₀, which, however, stands for the existing „coarse“ particle standard according to EPA.

such as sulphur oxides (SO₂, SO₃), nitrogen oxides (NO, NO₂), ammonia (NH₃) and Non-Methane Volatile Organic Compounds (NMVOC). Reaction products are ammonium sulphates and ammonium nitrate, aldehydes and ketones as an oxidation product of NMVOC. Greatest producer of secondary aerosols are stationary combustion processes (energy, industry, domestic fuel: SO₂, SO₃ and NO, NO₂), agriculture (NH₃), Diesel engines (NO_x), use of solvent, chemical industry and petro chemistry (NMVOC) [UBA 2005].

Long exposures to particulate matter can cause serious health problems such as higher morbidity, affection of lungs and a shorter life expectancy, mainly in subject with pre-existing heart and lung diseases. The particle size is a main determinant of health effects. Coarse particles are generally filtered in the nose and throat where as particulate matter smaller than PM₁₀ can settle in the lungs and may reach the alveolar region. The size PM₁₀ can't be seen as a strict edge between respirable and non-respirable particles, but has been agreed upon for monitoring by most regulatory agencies so far. WHO though has published 2006 it's latest Air Quality Guideline (AQGs) based on health effects with limiting values for PM₁₀ and PM_{2.5}, both for short-term and long- exposures [WHO 2006].

3.2 Health relevance of PM

The aim of the Air Quality Guideline (AQG) of the World Health Organization (WHO) is to support actions to achieve air quality that protects human health. Countries are encouraged by WHO to consider adopting an increasingly stringent set of standards, tracking progress through the monitoring of emission reductions and declining concentrations of particulate matter. To assist this process, the guideline and interim target values of the AQG reflect the concentrations at which increased mortality responses due to particulate matter air pollution are expected based on current scientific findings [WHO 2006]. Beside the guideline value, three interim targets were defined since countries may find these interim targets particularly helpful in gauging progress over time in the difficult process of steadily reducing population exposures to PM. Due to WHO's Air Quality Guideline both the European Commission and the United States Environmental Protection Agency have used the approach to revise their air quality standards for particulate matter. Table 3.1 and Table 3.2 summarize the current data on PM reported by WHO proposed for annual and daily mean concentrations.

Table 3.1 WHO air quality guidelines and interim targets for particulate matter: annual mean concentrations. The use of PM2.5 guideline value is preferred.

	PM10 [$\mu\text{g}/\text{m}^3$]	PM2.5 [$\mu\text{g}/\text{m}^3$]	Basis for the selected level
Interim target-1	70	35	These levels are associated with about a 15% higher long-term mortality risk relative to the AQG level.
Interim target-2	50	25	In addition to other health benefits, these levels lower the risk of premature mortality by approximately 6% [2–11%] relative to the IT-1 level.
Interim target-3	30	15	In addition to other health benefits, these levels reduce the mortality risk by approximately 6% [2-11%] relative to the IT-2 level.
Air quality guideline (AQG)	20	10	These are the lowest levels at which total, cardiopulmonary and lung cancer mortality have been shown to increase with more than 95% confidence in response to long-term exposure to PM2.5.

Table 3.2 WHO air quality guidelines and interim targets for particulate matter: 24 hour concentrations (99th percentile (days/year)).

	PM10 [$\mu\text{g}/\text{m}^3$]	PM2.5 [$\mu\text{g}/\text{m}^3$]	Basis for the selected level
Interim target-1	150	75	Based on published risk coefficients from multi-centre studies and meta-analyses (about 5% increase of short-term mortality over the AQG value).
Interim target-2	100	50	Based on published risk coefficients from multi-centre studies and meta-analyses (about 2.5% increase of short-term mortality over the AQG value).
Interim target-3	75	37.5	Based on published risk coefficients from multi-centre studies and meta-analyses (about 1.2% increase in short-term mortality over the AQG value).
Air quality guideline (AQG)	50	25	Based on relationship between 24-hour and annual PM levels.

3.3 Immission limit values for PM

Table 3.3 shows a comparison of immission limit values in different countries.

The European Community has set in directives 1999/30/EC and 96/62/EC limits for PM₁₀ in the air. On Jan. 1st 2005 these standards became effective. In a first phase the limit of the yearly average is 40 µg/m³ and for daily average (24 hour mean) 50 µg/m³. The daily average is not allowed to be exceeded more than 35 times per year. In a second phase starting June 1st 2010 the yearly average standard will be 20 µg/m³ and the daily average limit 50 µg/m³ where as the allowed number of daily exceedances will be reduced to 7 days per year.

Table 3.3 Immission limit values for PM10 (except USA: PM10 and PM 2.5). *indicative value

Country	Annual limit value [µg/m ³]	24 hour limit value [µg/m ³]	Allowance for 24 h limit value
EC to 1.6.10	40	50	35 exceedances p.a. (Austria: 30)
EC from 1.6.10	20	50	7 exceedances p.a. (Austria: 25)
Switzerland	20	50	1 exceedance p.a.
Norway	35	50	
WHO (AQG)	20	50	
WHO (AQG)	10	25	
USA PM ₁₀		150	1 exceedance p.a.on average over 3 a
USA PM _{2.5}	15	65	98% for an average over 3 a

4 Combustion particles

4.1 Types of combustion particles

Investigations on particle emissions showed, that well designed and properly operated automatic wood combustion plants achieve a high combustion quality thus resulting in low emissions of unburned hydrocarbons and soot [Nussbaumer 2005]. However, automatic wood boilers exhibit fairly high mass concentrations of particle emissions in the raw gas, i.e., typically in the order of magnitude of 100 mg/m^3 at 13 Vol.-% O_2 for natural wood chips and up to several 100 mg/m^3 for other fuels such as bark. Particles from well designed and operated automatic wood combustion consist mainly of inorganic matter such as salts, while particles from wood stoves operated under poor conditions consist mainly of soot and organic substances.

Typical inorganic particles in the flue gas of a well operated automatic combustion devices are shown in Figure 4.1. From a poorly operated wood stove, soot particles as well as tar droplets can be identified as shown in Figure 4.2. In conditions with lack of oxygen in the combustion chamber, the mass concentration on total particle mass increases dramatically as shown Figure 4.3, which is due to unburnt soot in the flue gas. As a result of agglomeration, the particle size distribution is shifted to larger particles. In addition, high concentrations of condensable organic matter are released with the flue gas.

Soot from diesel engines has been identified as being carcinogenic in many investigations. However, particulate matter from incomplete combustion of wood consists of solid soot particles and condensable organic substances. Hence significantly higher concentrations of toxic polycyclic aromatic hydrocarbons (PAH) as well as far higher cell toxicity and carcinogenic potential were found in particles and condensables from incomplete combustion of wood than in diesel soot [Klippel & Nussbaumer 2007 a].

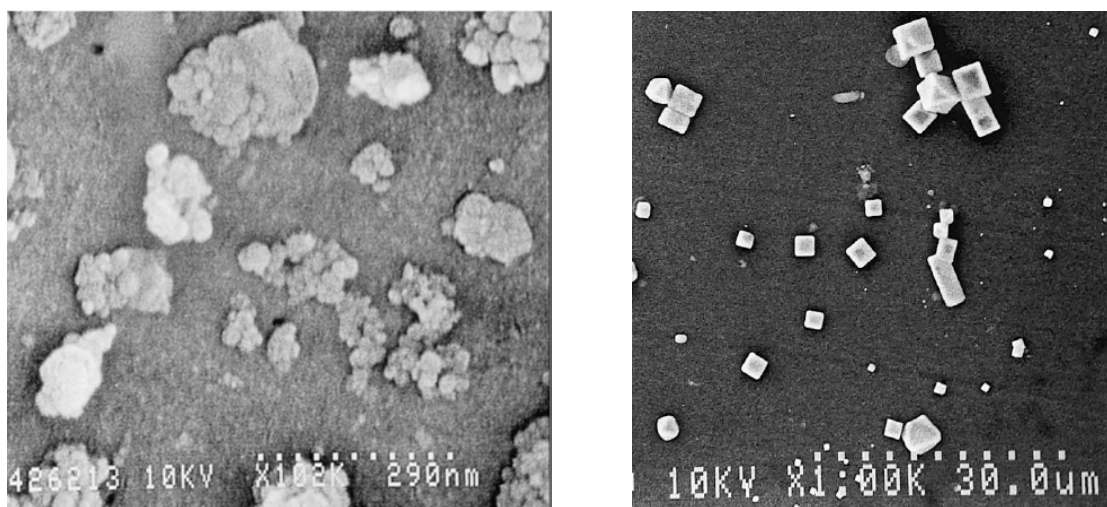


Figure 4.1 SEM-pictures of particles in the flue gas of an automatic wood combustion system, left from the combustion of wood resulting in submicron particles, right from the combustion of herbage grass resulting in larger particles at higher mass concentrations [Kaufmann et al. 2000].

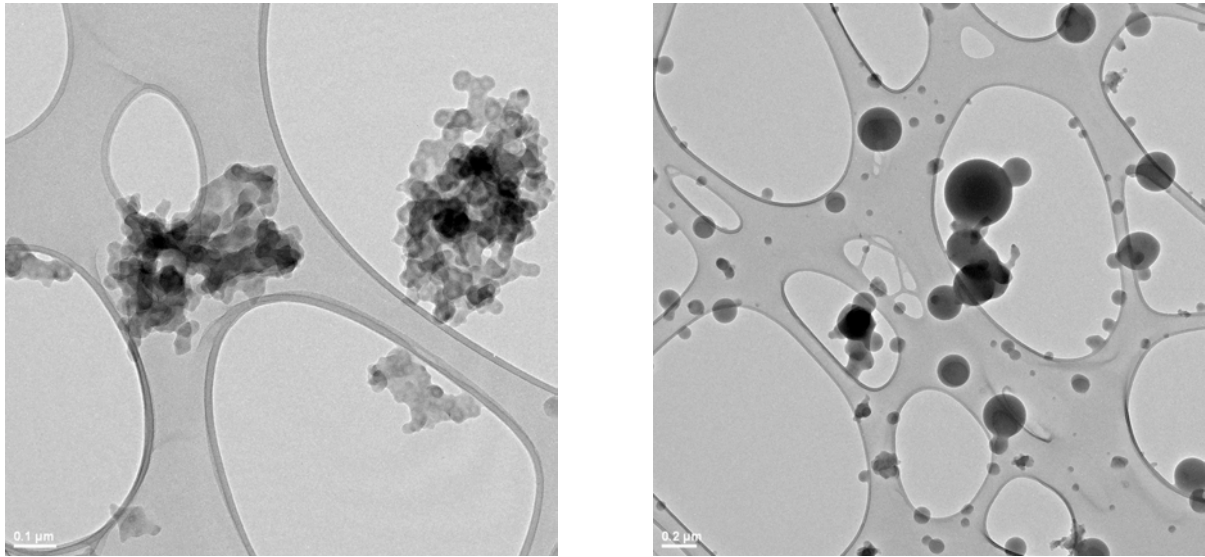


Figure 4.2 TEM-pictures of soot agglomerates (left) and tar droplets (right) from the flue gas of a poorly operated wood stove. Scale of white line in the left picture: 100 nm, right: 500 nm. Pictures from Heuberger, EMPA Dübendorf, published in [Klippel & Nussbaumer 2007 b].

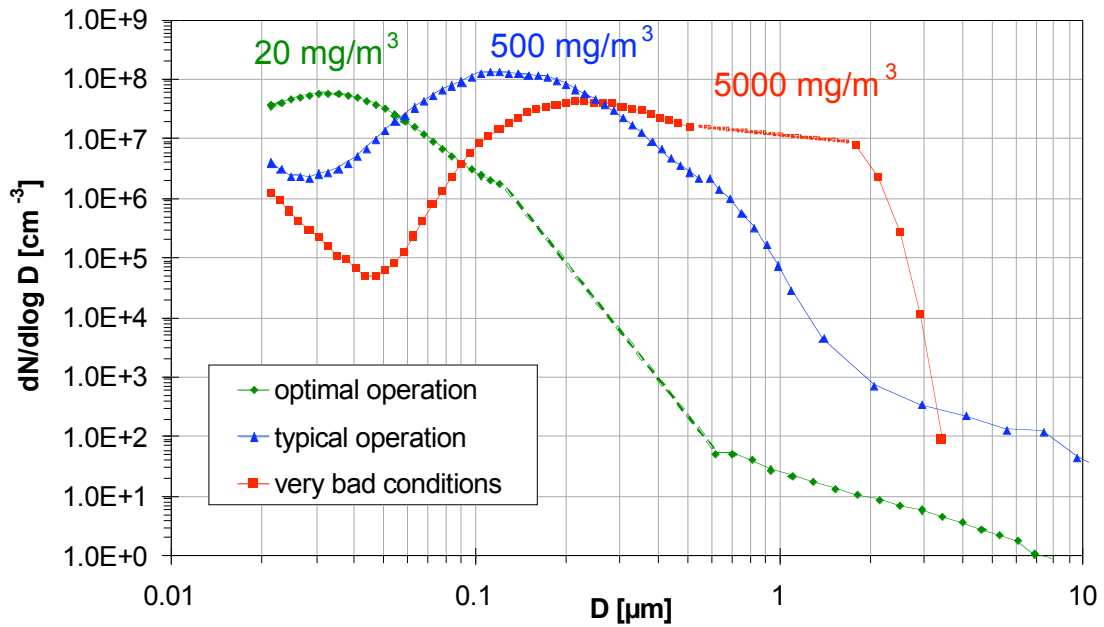


Figure 4.3 Number size distribution of particles from wood stoves under different operation conditions monitored in the size range from 20 nm to 10 μm by Scanning Mobility Particle Sizer (SMPS) and Optical Particle Counter (OPC). Mass concentrations measured with gravimetric method according to VDI and indicating only solid particles without condensables at 13 Vol.-% O_2 [Klippel & Nussbaumer 2007 b].

4.2 Influence of particle sampling

Combustion particles are a mixture of solid particles and condensables, both containing organic and inorganic fractions. Especially the organic emission is strongly influenced by the combustion conditions. High organic emissions are correlated with low combustion efficiency and high potential for toxic organic substances, e.g. benzo(a)pyrene (BaP) or fluorene and can be avoided by high combustion temperature, sufficient oxygen availability in the flame enhanced by good mixing and sufficiently long residence time in the combustion zone.

The emission of inorganic particles can be slightly influenced by the combustion conditions, however it depends on different formation mechanisms. High temperature typically enhances the conversion of ash material to the gas phase and consequently the emission of inorganic particles. Under typical conditions, organic particles are most relevant in poorly operated manual wood combustion devices, while inorganic particles are most dominant in automatic wood combustion plants operated at high temperatures. Depending on the aim of the measurement, different sampling strategies are commonly used e.g. for product testing and health studies. In the present survey, three types of particle sampling are distinguished as illustrated in Figure 4.4:

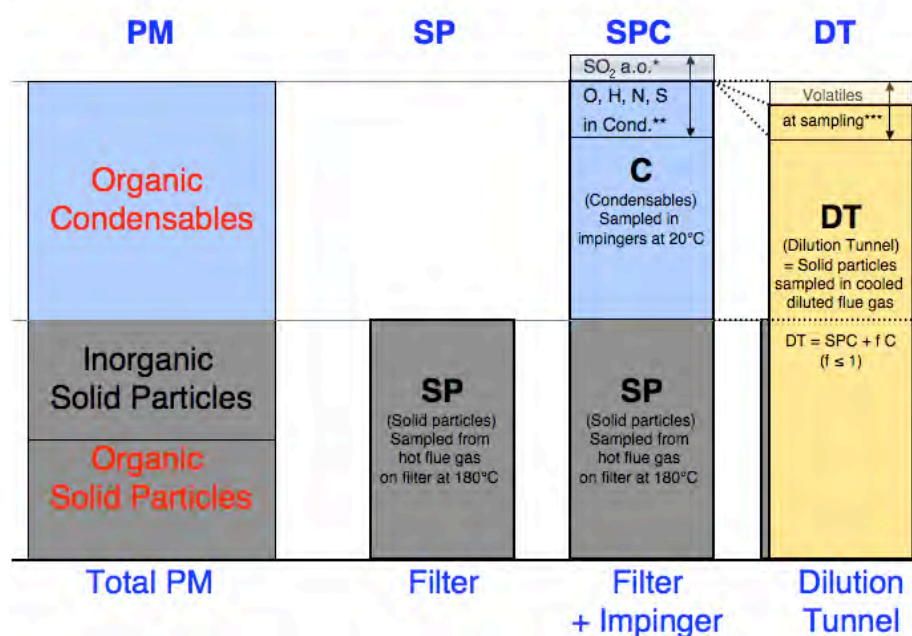


Figure 4.4 Comparison of different sampling methods with total PM in the flue gas. Explanations:
PM: Total Particulate Matter in flue gas at ambient temperature.
SP: Filter (Method a) resulting in solid particles SP.
SPC: Filter + Impinger (Method b) resulting in solid particles and condensables SPC.
DT: Dilution Tunnel (Method c) resulting in a PM measurement including SPC and most or all C. Hence DT is identical or slightly smaller than SPC + C due to potentially incomplete condensation depending on dilution ratio and sampling temperature (since dilution reduces not only the temperature but also the partial pressure of contaminants).

*SO₂ and other soluble gaseous compounds in the flue gas may be dissolved in the impingers.

**In case of determination of TOC in impingers, the mass of O, H, N, S and other elements contained in the organic condensables needs to be accounted for separately.

***Organic compounds which are liquid or solid at partial pressure in the flue gas and ambient temperature but volatile at sampling due to reduced partial pressure by dilution and temperature above ambient.

- a) Sampling of particles on a heated filter, through a probe, from undiluted flue gas in the chimney at gas temperatures of e.g. 180°C (VDI) or 120°C (EPA). These particles are defined as **solid particles (SP)** in the study and consist of filterable particles and droplets at the indicated temperature. If not indicated otherwise, data on PM in the present report are given as SP. Solid or filterable particles consist of inorganic particles and organic particles. The inorganic particles are constituted to a large part of K_2SO_4 and KCl (depending on the fuel composition) at favourable combustion conditions, while soot (elemental carbon, EC) and organic particles are also emitted as solid particles if the combustion conditions are poor.
- b) Sampling of particles as described in a) and subsequent sampling of **condensable organic matter (C)** in impinger traps at temperatures $< 20^\circ\text{C}$. Typically condensable particulate emissions are sampled in a series of impinger flasks, e.g. containing water to collect inorganic compounds and containing methylene chloride to capture organic compounds. The sum of **solid particles and condensables** are defined as **(SPC)** in the present report. Inorganic matter, excluding water, found in the impingers can originate from gaseous products such as e.g. SO_2 . Hence in case of relevant amount of such compounds, the allocation of the respective mass to either gaseous or particulate emissions is uncertain and needs further information. Under typical wood combustion conditions, the inorganic PM is sampled in the filter, while condensable inorganic matter in the impinger bottles is assumed to be negligible.
- c) Sampling of filterable particles in a dilution tunnel with a filter holder gas temperature $< 35^\circ\text{C}$ (e.g. Norwegian standard NS 3058-2). Due to the cooling and dilution, condensable organic material in the hot flue gas condenses on the filter. Condensable inorganic PM is assumed to be negligible for residential combustion of wood. Hence the particle concentration found by method c) is assumed to be similar or equal to the mass detected by method b). The particles detected by method c) are defined as particles in **dilution tunnel (DT)** in the present study.

For residential combustion devices, all three methods can be applied, while for large combustion devices, method c is not applicable.

Method a is useful for testing of combustion devices, but can significantly underestimate the total organic PM in ambient air resulting from biomass combustion for applications with high concentrations of organic substances resulting from incomplete combustion. Since condensable organic matter has been identified as highly toxic, method a may not only underestimate the mass concentration of PM but in addition the environmental impact.

4.3 Measurement techniques

Table 4.1 shows a comparison of the most common methods for discontinuous measurements of particulate emissions, while Table 4.2 shows an overview on the covered size ranges and the advantages and disadvantages of continuous measurement methods.

Discontinuous gravimetric sampling of total particle mass concentration

The basic method to measure mass concentrations of PM off-line in flue gases is gravimetric sampling on quartz or glass fibre **filters**, which have been in a desiccator or a room with controlled humidity prior to sampling. This method gives total mass concentration. As an option, mass concentration of a specific size fraction can be gathered in combination with a precyclone with a cut-off of e.g. 10 μm or 2.5 μm thus resulting in PM_{10} or $\text{PM}_{2.5}$. The sampling of particles on filters enables typical time resolution of 15 minutes and up and hence does not enable to identify fast processes. However, particles available on the filter are potentially available for additional chemical analysis.

Continuous measurements of particulate matter

When there is a need of real-time measurements of PM_{10} and $\text{PM}_{2.5}$ **Tapered element oscillating micro-balance (TEOM)** is a well established instrument. TEOM is often used for control of PM_{10} and $\text{PM}_{2.5}$ in ambient air. In combustion applications, the ambient air model of the instrument is used together with a dilution system. For larger combustion plants, there is a specific model of TEOM available which operates without dilution.

Measurements of particle size distributions

Since the particle size is an important parameter which influences e.g. the lifetime of the particles in the ambient air and the separation efficiency in the human respiratory tract, there is an increasing interest in the particle size of particulate emissions as well as of particulate matter in the ambient air. For this purpose, particle number or particle mass distributions are determined depending on the analytical method. In addition, on-line detection with high time resolution is of interest to detect stationary combustion processes such as e.g. the start-up phase of combustion devices.

a) Mass size distribution

For measurements of mass size distributions, low pressure **cascade impactors** (e.g. Andersen Impactor, Dekati Low Pressure Impactor DLPI, Berner Low Pressure Impactor BLPI) are frequently used, typically ranging from 30 nm to 10 – 20 μm , sometimes also combined with a filter which extends the measurement range down to a few nanometres. Due to the sampling method, cascade impactors are also operated off line and particle samples can potentially be used for additional analyses.

b) Number size distribution

From health aspects there is also an interest in particle number concentrations and particle number size distributions, since a high number of ultrafine particles are assumed to be relevant at least to certain health issues. There are several instruments available for on-line measurements of particle number, mostly in need of dilution systems as they do not cope with high temperatures. The main instruments are:

- **Scanning mobility particle sizer (SMPS)** are commonly used for measurement of number concentration and corresponding size distribution. There are a number of instrument versions, working in the size range from a few nanometres to 1 μm .
- **Electric low pressure impactor (ELPI)** is another instrument for characterisation of number concentration and distribution, ranging from 7 nm to 10 μm .
- **Aerodynamic particle sizer (APS)** measures particles from $\sim 0.5 \mu\text{m}$ to $\sim 10 \mu\text{m}$.
- **Fast mobility particle sizer (FMPS)** is a rather new instrument for number concentrations and size distributions ranging from 5.6 nm to 0.56 μm .
- **Optical particle counter (OPC)** is another option for measurement of number of particles, typically ranging from $\sim 0.1 \mu\text{m}$ to a few micrometers.

The instruments mentioned use different particle diameters for characterisation of number size distributions. It is important to respect which diameter is considered e.g. to perform calculations from number to mass concentration. In Figure 4.5 a comparison of SMPS, ELPI, DLPI, and APS is presented in which all data are converted to aerodynamic diameter by assumption of spherical particles with an equivalence density of 2 g/cm³ for SMPS and ELPI. With this assumption, ELPI and SMPS show a reasonable agreement in the submicron range. In the supermicron range, measurements with ELPI lead to far higher values than DLPI and DLPI leads to far higher values than APS. However, it needs to be respected, that the presented data exhibit a very steep decrease in concentration between 0.1 to 10 μm as they cover a total range in concentration of 9 orders of magnitude. Due to the measurement principle of successive separation of particles with decreasing size as used by SMPS and ELPI, it is difficult to cover many orders of magnitudes in concentration, since a minor carry-over of small particles to the subsequent separation sections lead to a significant over estimation of the number of large particles. Hence the ELPI over estimates the number concentration in Figure 4.5 for particles $> 0.5 \mu\text{m}$. This effect has also been found for a comparison of SMPS and OPC, where in case of moderate particles concentrations $> 0.2 \mu\text{m}$ (i.e., for good combustion conditions), the SMPS was over estimating the number concentrations $> 0.2 \mu\text{m}$, while SMPS and OPC showed good agreement in the range between 0.1 to 0.5 μm in case of high concentrations (i.e., poor combustion conditions) [Klippel & Nussbaumer 2007 b]. In such applications, OPC measurement needs to be performed in diluted flue gas to avoid exceedance of the measurement limit, where two particles may be detected as one.

Additional particle properties

Besides mass and number concentrations surface and volume concentrations are examples of other parameters that might be interesting to consider in certain applications. Finally, it should also be emphasized that characterisation of chemical content is very important as it can give information on combustion conditions and mirrors the ash content in the fuel.

Table 4.1 Comparison of methods for discontinuous particle measurements [Jokiniemi 2007]. LPI = Low pressure impactor, SEM/TEM = Scanning electron microscopy/tunnel electron microscopy.

Device	range	parameters	+	-
Filter sample	depends on pre-cutting	mass concentration	simple, reliable	lots of work
LPI	0.03 - 10 μm <0.03 μm (filter stage)	mass distribution		lots of work
SEM/TEM	-	morphology, particle size, elements can be analyzed		sensitive to amount of sample
Denuder method [annular denuders+ filter+PUF]	depends on pre-cutting	gas-particle distribution of organic compounds	no artefacts due to adsorption of gaseous compounds on filter or evaporation of particle-phase compounds	lots of work particle losses

Table 4.2 Comparison of methods for continuous particle measurements [Jokiniemi 2007].

Device	range	parameters	+	-
FMPS	0.007 - 700 μm electrical mobility d_p	number concentration number distribution	fast, indicates changes in process well	more inaccurate than SMPS
SMPS	0.005 - 1 μm 0.003 - 0.09 μm electrical mobility d_p		very small particles	scanning time (problem in varying combustion process)
ELPI	0.03 - 10 μm 0.07 - 6.6 μm (fs) aerodynamic d_p		robust indicates changes in process well, large size range	wide channels plates may affect the result
TEOM	depends on pre-cutting	mass concentration	agrees well with filter samples	if concentration is high, filter has to be changed

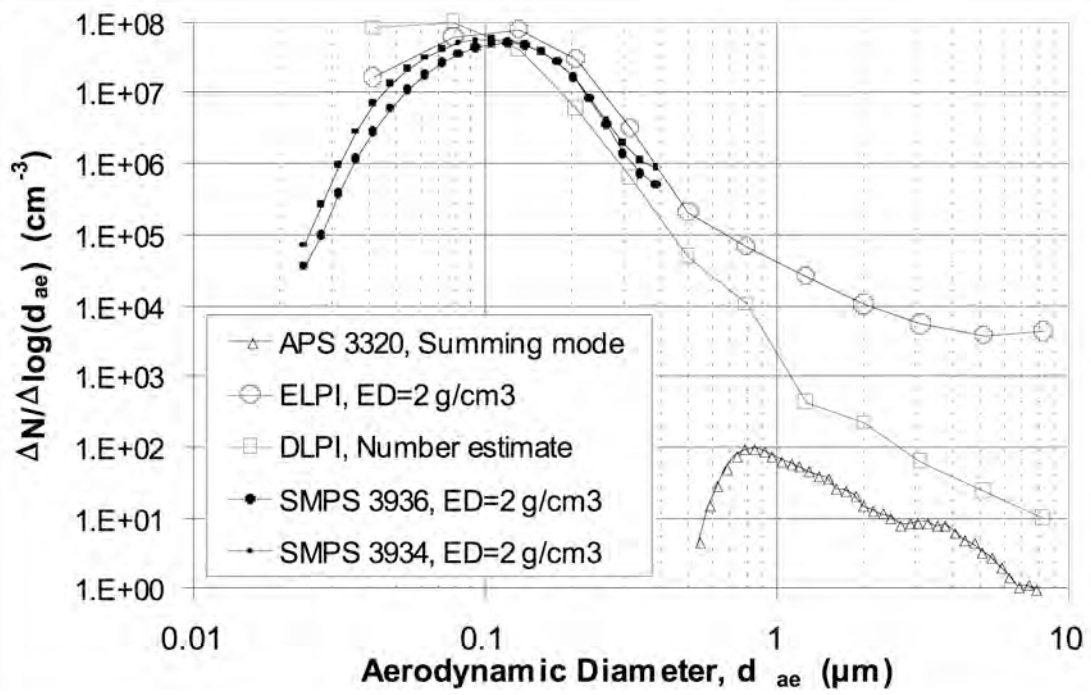


Figure 4.5 Comparison of number size distributions with different measurement instruments at simultaneous measurement in flue gas from a residential pellet burner [Pagels et al. 2002].

5 Data basis

5.1 Participating countries

In total, 17 participants from 7 countries participated in the present survey and contributed with data in the questionnaire. In addition, data for national emission factors were reported or gathered from literature.

Table 5.1 List of participating IEA countries and institutions in the survey.

Country	Abbreviation	Institution (full name)
AUS	BLT	Biomass Logistics Technology, Wieselburg
	Bios	Bios Bioenergy and Graz University of Technology, Graz
	Joanneum	Joanneum Research, Graz
	KOV	Austrian Tiles Stove Association, Vienna
DEN	Force	FORCE Technology, Brøndby
GER	IE	Institute for Energy and Environment, Leipzig
	TFZ	Technologie- und Förderzentrum, Straubing
	Uni Stuttgart	University of Stuttgart, Inst. of Process Eng. and Power Plant Technology
	ZAE	ZAE Bayern, Garching
NET	TNO	TNO Science and Industry, Apeldoorn
NOR	SINTEF	SINTEF NBL, Norwegian Fire Research Laboratory, Trondheim
SWE	SP Tech.	SP Technical Research Institute of Sweden, Borås
	Umeå Uni	Umeå University, Energy Techn. and Thermal Process Chemistry, Umeå
	VXU	Växjö University, Dep. of Bioenergy Technology, Växjö
SWI	CATSE	Centre of Appropriate Technology and Social Ecology, Langenbruck
	Verenum	Verenum, Zürich and University of Lucerne, Lucerne
	Vock	Vock Engineering, Maschwanden

5.2 Sources

Most of the data presented in the following figures have been indicated by the participating experts from the institutions described in Table 5.1. In these cases, there is no direct literature quotation, as these data have been collected by the questionnaire sent out in the present study.

In several cases, additional data have been used from reports or literature. In these cases, the source is cited in the figures with numbers in brackets as e.g. [7] which refer to the literature list in chapter 9.2.

5.3 Emission factors

Emission factors are representative values which attempt to relate the quantity of a pollutant released to the atmosphere with an activity associated with the release of that pollutant [EPA 2007]. Emission factors for biomass combustion appliances are expressed as the weight of pollutant divided by a unit energy, volume, or weight of the activity emitting the pollutant (e. g., grams of particulate emitted per kilogram of wood burned). They are used to make source- or appliance-specific emission estimates.

Emission factors represent an average range of emission rates, roughly half of the subject sources will have emission rates greater than the emission factor and the other half will have emission rates less than the factor. Manual operated combustion appliances have an especially wide range of emission factors. Essential are the operating mode, the fuel type, and the technique of the equipment. Measures regarding manual operated combustion devices show that the emissions during practical operation have a factor leastwise twice as high as during ideal operation whereas by improper handling the emissions can possibly be even ten times as high. The accuracy of emission factors has a central impact on the quality of emission inventories.

To obtain a clearer picture of the emission range, one target of the survey is to record values containing data from best results at ideal operation over typical results at practical operation to worst results at very poor operation. The collected emission factors are results of measurements and data from literature of various countries and where delivered in different measures. For comparison reasons the data are converted to mg particles emitted per MJ end energy contained in the fuel based on lower heating value and indicated as [mg/MJ]. If not determined in the evaluated literature, emission factors are assumed to be measured without start.

6 Results on emission factors

6.1 Open fireplaces

Figure 6.1 shows the PM emission factors for open fireplaces. The range for typical measured emission factors on solid particles (SP) varies between 23 and 265 mg/MJ. National emission factors range from 160 (GER) to 447 mg/MJ (UKM). The official emission factor for Finland and Norway are 860 mg/MJ and 910 mg/MJ respectively indicated for measurements with dilution tunnel (DT).

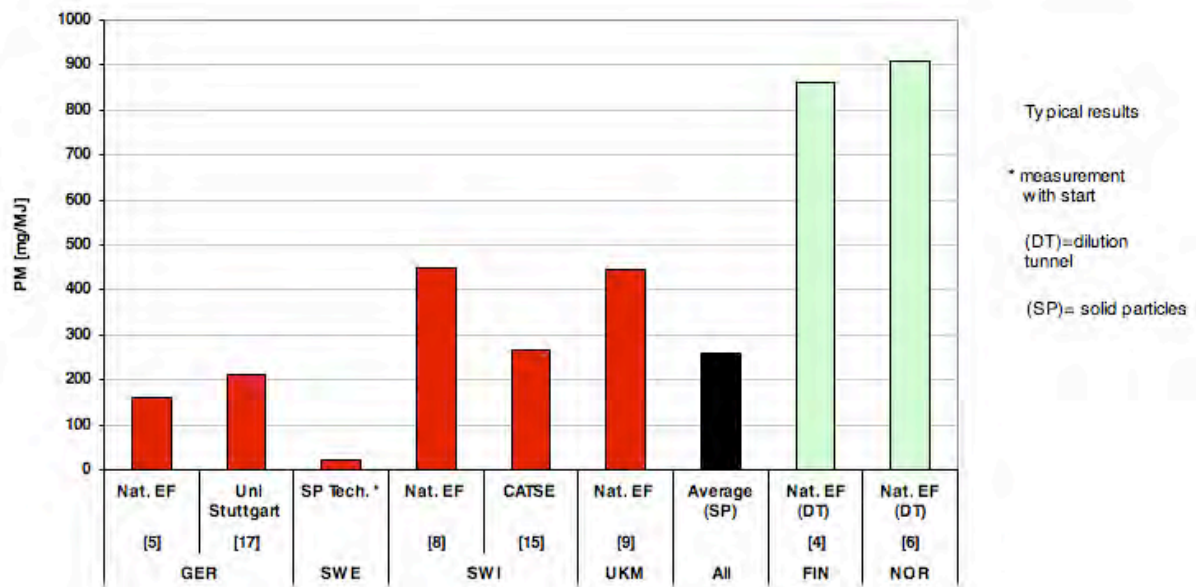


Figure 6.1 Emission factors for PM in mg/MJ for solid particles (SP, red) and for particles measured in dilution tunnel (DT, light green).

6.2 Closed inset appliances (closed fireplaces)

For closed inset appliances (closed fireplaces according to EN 13229:2001), only few data were available. Worst results for emission factors range from 180 – 204 mg/MJ, typical results from 47 – 83 mg/MJ and best results from 14 – 26 mg/MJ.

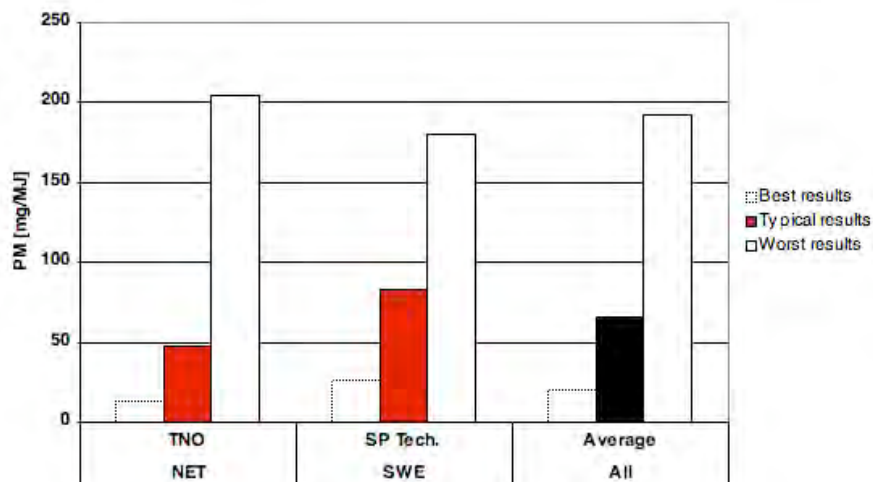


Figure 6.2 Emission factors for closed inset appliances indicated as solid particles (SP).

6.3 Wood stoves

In this paragraph, PM emission factors for conventional wood stoves with natural draft are discussed. Within the survey most data was delivered for the category of wood stoves so that this rubric represents a broad overview. For typical measured solid particles with start phase the scope ranges from 64 to 87 mg/MJ. Measurements with condensables and in dilution tunnel show persistently higher results in the range from 340 to 544 mg/MJ.

National emission factors are the basis for calculations of emission inventory reports. One of the most important applications is the reporting of national greenhouse gas inventories under the United Nations Framework Convention on Climate Change. The comparison of default PM emission factors for wood stoves reveals a wide order of magnitude. The emission factor for solid particles ranges from 94 mg/MJ (Germany) to 650 mg/MJ (Sweden). In countries with compulsory measurements with dilution tunnel the factors are higher compared to solid particles. Factors vary from 750 mg/MJ (Finland) to 1932 mg/MJ (Norway). The Finnish value is a new revised number which will apply soon, while currently the old value of 400 mg/MJ is still in force. The Norwegian emission estimate is based on an aggregated emission factor for traditional/conventional stoves, new stoves and open fireplaces [Nordic Council of Ministers 2004]. An explanation to the high Norwegian emission data is that the Norwegian standard for wood stoves includes measurements at low thermal output with throttled air supply. Thus the data should represent real use of wood stoves in Norway.

Figure 6.3 shows the emission factors for wood stoves with indication of ranges from best, typical to worst type of operation or combustion type. Figure 6.4 summarizes the same data with indication of the typical data only. Figure 6.3 and Figure 6.4 are given additionally in magnified scale in the appendix for better readability.

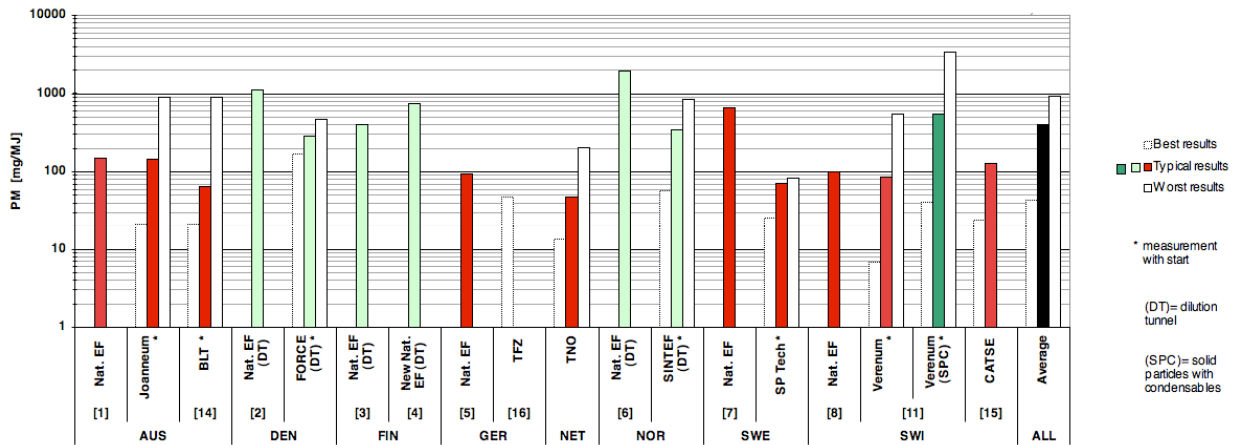


Figure 6.3 Range of emission factors from worst to best (where available) for wood stoves depending of type of operation and/or equipment. Red = SP, light green = DT, dark green = SPC, black = average.

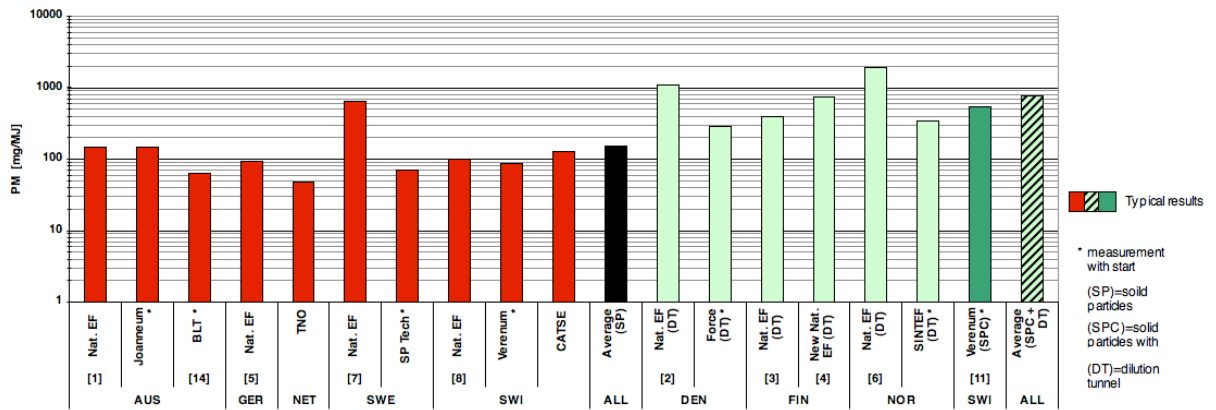


Figure 6.4 Average emission factors for wood stoves. Red = SP, light green = DT, dark green = SPC, black = average SP, black and green = average SPC and DT.

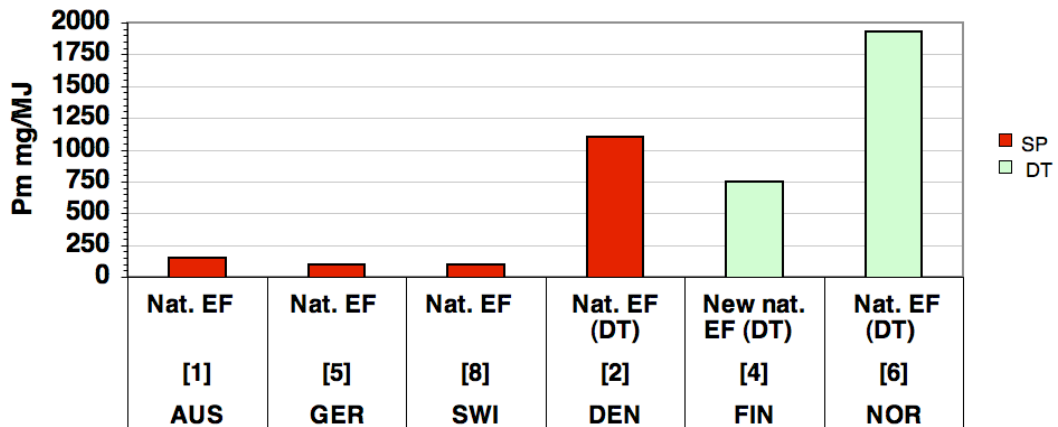


Figure 6.5 National emission factors for wood stoves.

6.4 Log wood boilers

For log wood boilers, the technology of two stage combustion has been implemented since more than 20 years. Most modern log wood boilers used e.g. in Switzerland, Austria, and Germany are based on a two stage combustion with primary air for the solid fuel conversion, a subsequent mixing zone with injection of secondary air followed by the post combustion chamber and finally the heat exchanger in the boiler section [Nussbaumer 2003]. Such boilers are usually designed by the downdraft principle and most commonly operated with forced draft, either by application of ventilators for the air inlet and/or for the flue gas exhaust. In the present survey, data from downdraft boilers with forced draft and data from updraft boilers were collected.

Figure 6.6 shows the range of emission factors for updraft boilers, although available from a limited number of institutions only. If compared to data from the same countries, updraft boilers exhibit comparable ranges of emissions as wood stoves.

Figure 6.7 shows emission data from log wood boilers with forced draft. Under typical operation conditions, boilers with downdraft principle enable significantly lower emissions than updraft boilers.

Beside the combustion principle, the hydraulic implementation of the boiler in the heating system and in particular the application and management of a heat storage tank can significantly influence the emissions in practical operation. Figure 6.8 shows a comparison of emission factors of log wood boilers with and without heat storage tank. The combination of a log wood boiler with a heat storage tank enables an operation at full load or at stationary part-load with low emissions. On the other hand, boilers operated for house heating without heat storage tank may be used with throttled air inlet thus leading to excessively high emissions of unburnt carbon and particles.

Figure 6.9 shows an overview of data from log wood boilers, where no information about the combustion principle was available.

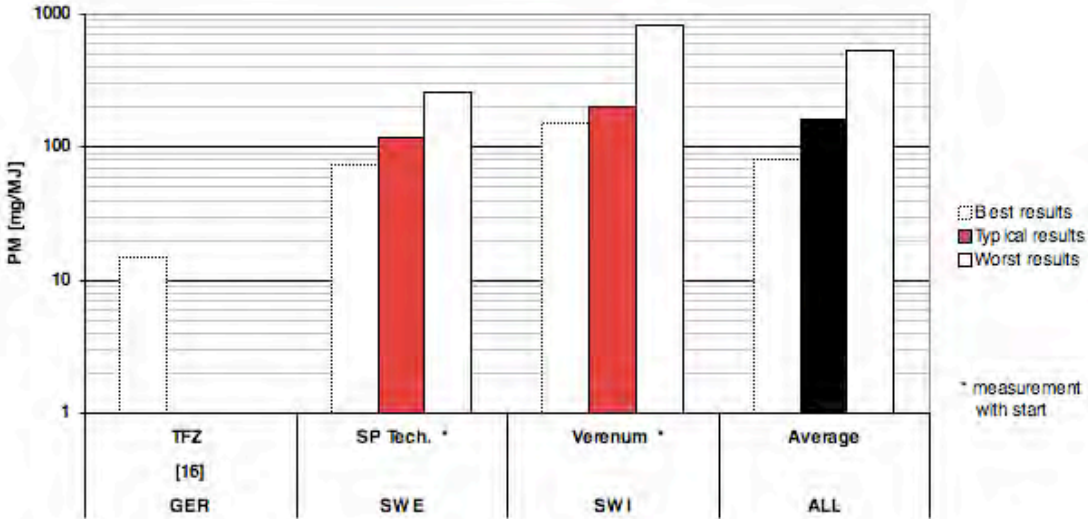


Figure 6.6 Range of emission factors from worst to best (where available) for log wood boilers with updraft combustion without ventilator.

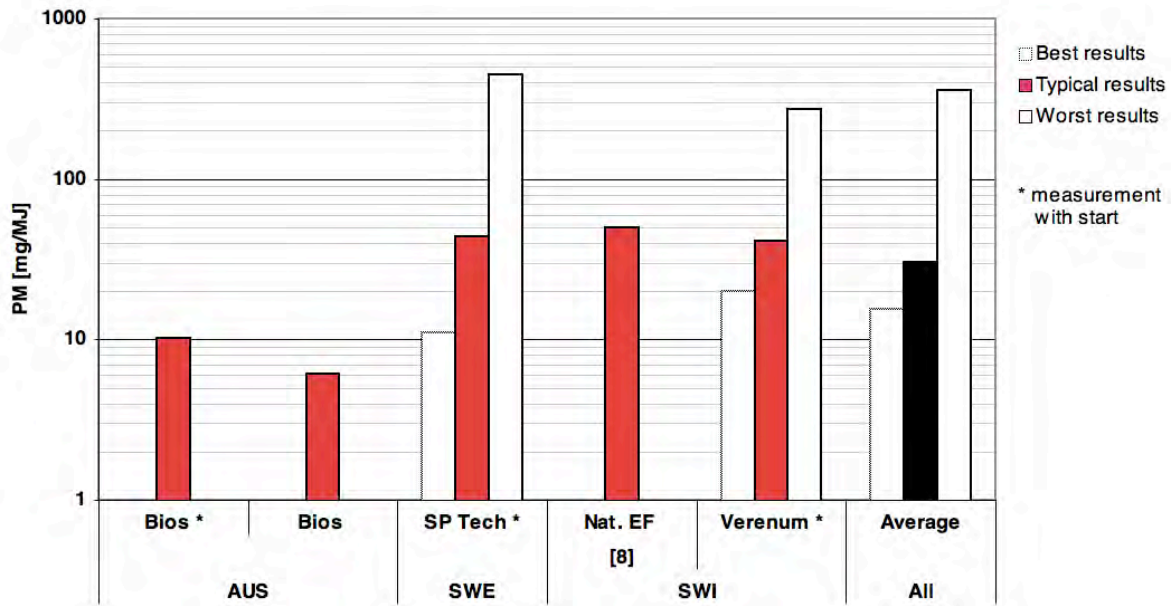


Figure 6.7 Range of emission factors from worst to best (where available) for log wood boilers with forced downdraft combustion.

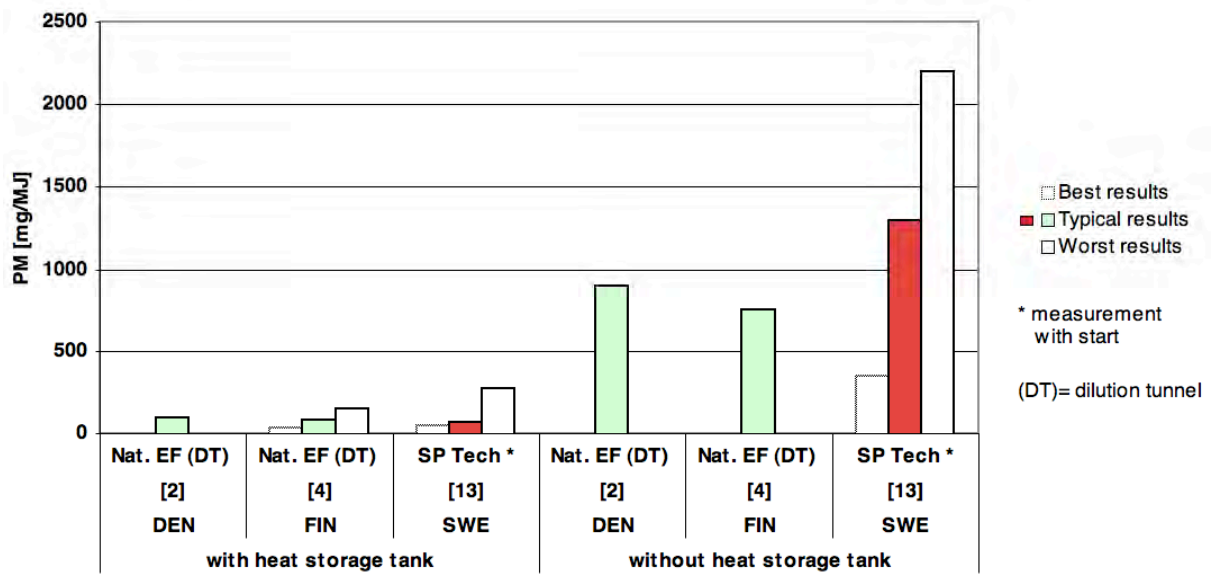


Figure 6.8 Emission factors for log wood boilers with and without heat storage tank.

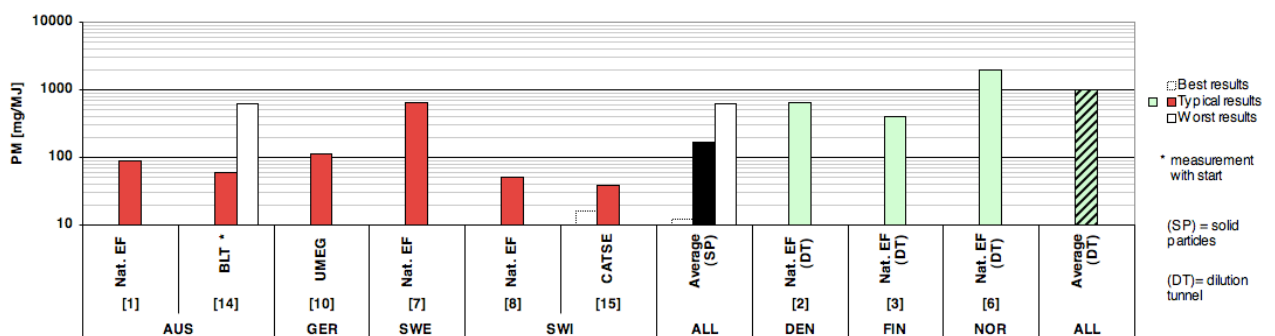


Figure 6.9 Emission factors for log wood boilers, where combustion type is not specified.

6.5 Pellet stoves and boilers

Figure 6.10 and Figure 6.11 show the emission factors of pellet stoves and pellet boilers respectively. For both applications, only results from the operation with pellets made from wood with low bark content are respected. The emission factors for pellet combustion are in most cases between 10 mg/MJ and 50 mg/MJ for typical operation and hence comparable to the best results achieved by log wood combustion. If worst results under poor operation conditions are compared, a relatively moderate increase in emissions is expected for pellet combustion. In comparison to log wood combustion, emission factors at non-ideal operation are at least an order of magnitude lower, which is regarded as the main advantage of pellet combustion.

However, many investigations have shown, that the utilization of other biomass than wood with low amounts of bark for pellet combustion in residential heating appliances results in significantly increased emissions of particulate matter (i.e. typically by a more than a factor of 3) as well as in emission of NO_x. Hence the reported data are valid for wood pellets with low ash content only.

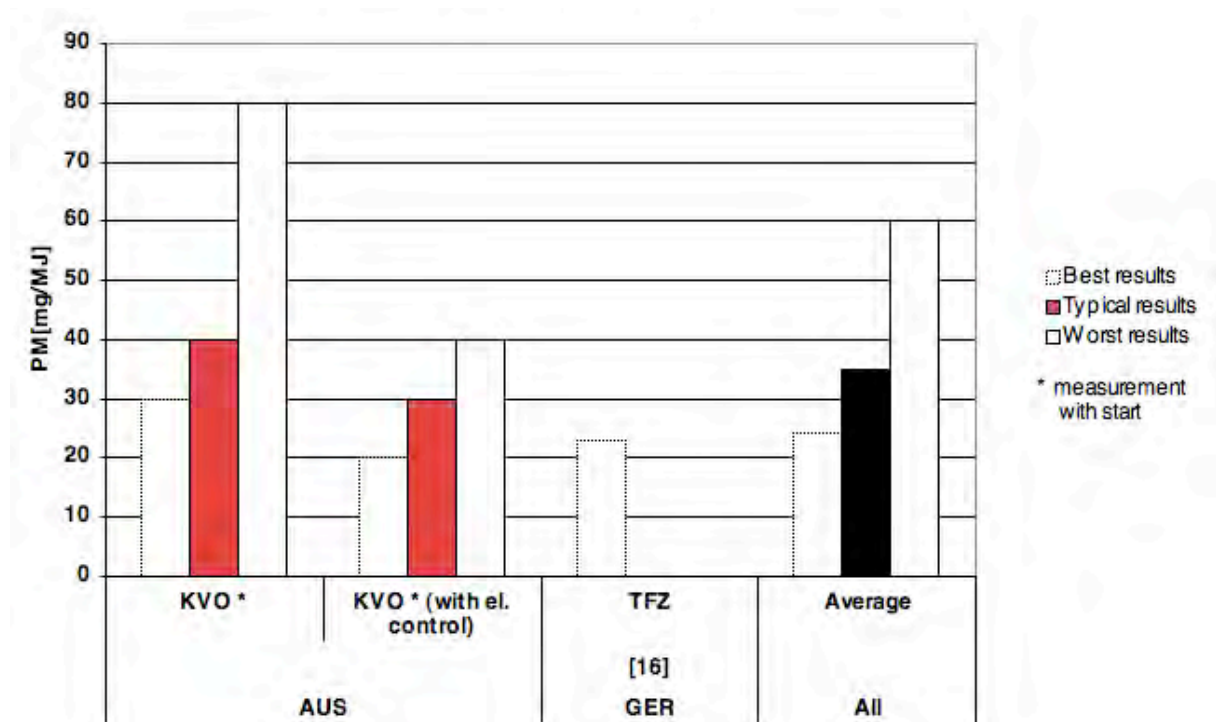


Figure 6.10 Range of emission factors from worst to best (where available) for pellet stoves with natural draft.

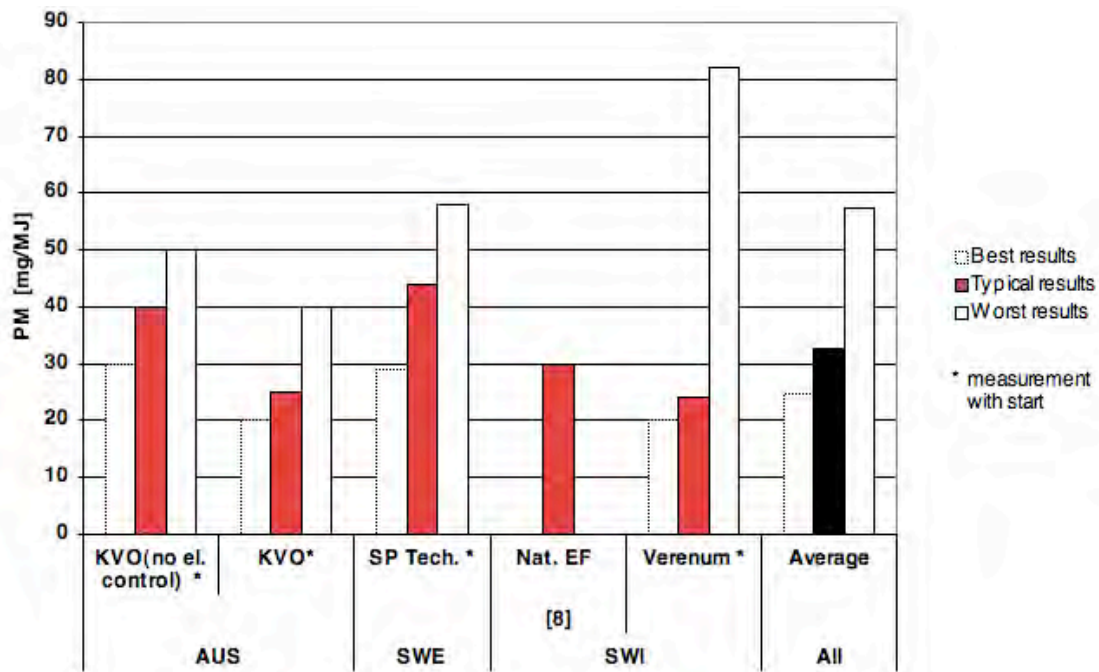


Figure 6.11 Range of emission factors from worst to best (where available) for pellet stoves with forced draft and electronic combustion control.

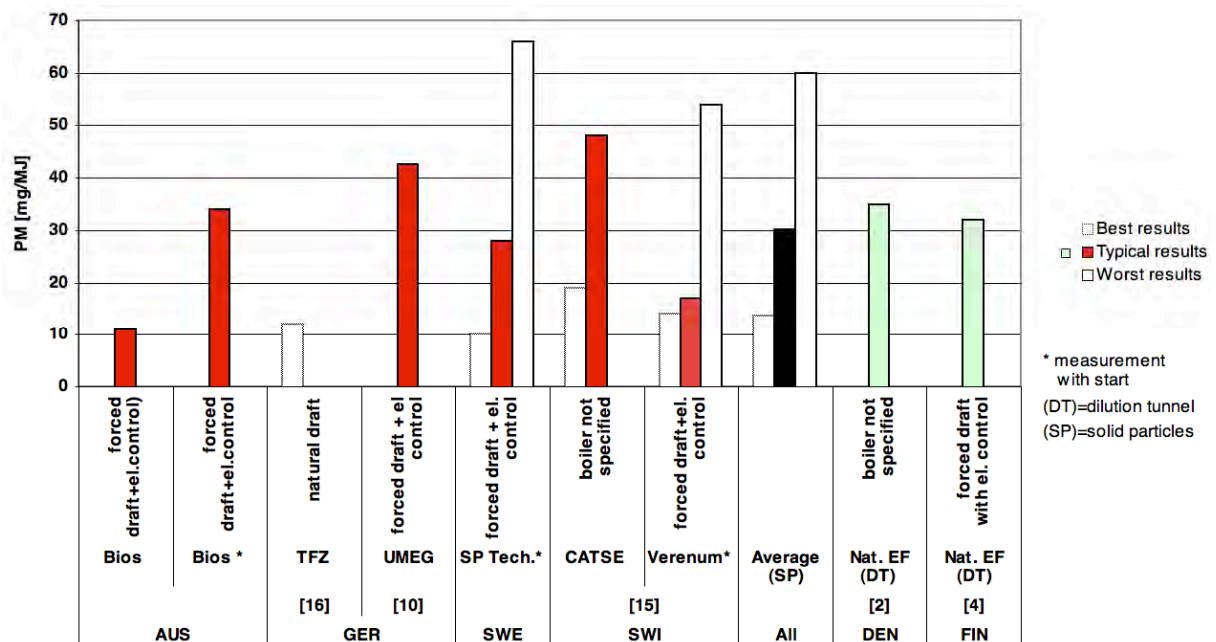


Figure 6.12 Range of emission factors from worst to best (where available) for pellet boilers.

6.6 Overview on residential wood combustion

Figure 6.13 gives a summary of the average emission factors for pellet combustion, log wood boilers, and wood stoves and shows the following results:

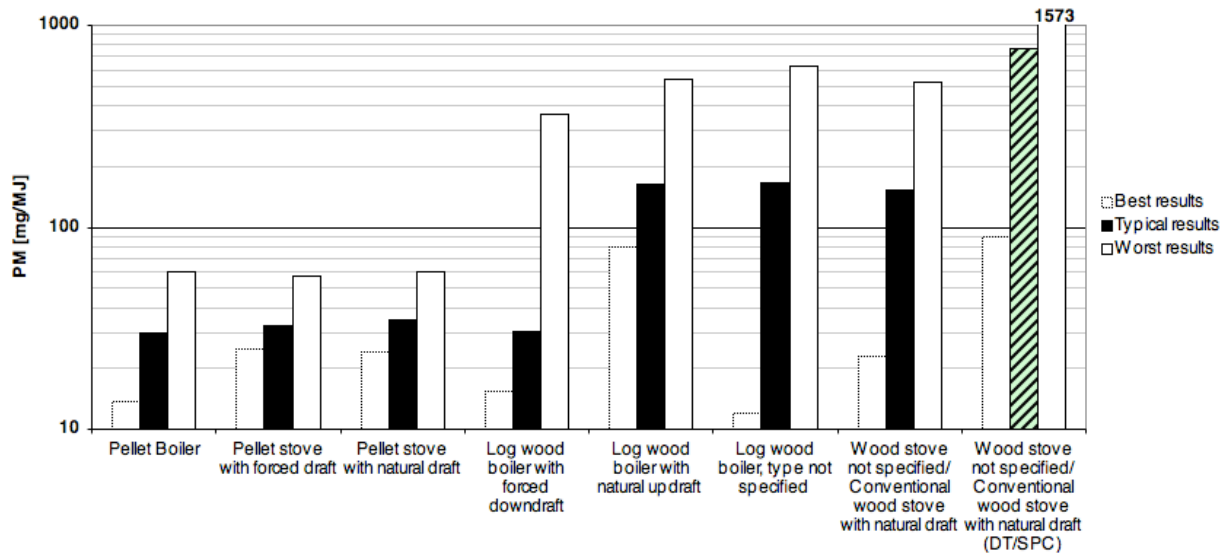


Figure 6.13 Average emission factors (best, typical, worst) for pellet boilers, pellet stoves, log wood boilers, and wood stoves. All data indicated as solid particles SP except for wood stoves, where data including condensables (SPC) or measured in dilution tunnel are given additionally in the last column.

- Pellet combustion and log wood boilers with forced draft achieve relatively low particle emissions not only under ideal operation conditions, but also under operation conditions which are assumed to be typical and should reflect the emissions under practical conditions of most installed heating devices of the respective categories. The reported data lead to an estimated average emission factor of approximately 30 mg/MJ indicated as filterable or solid particles (SP) for these categories under typical operation conditions. However, these emission factors are valid for natural, uncontaminated dry wood only, while significantly higher emissions are found for other fuels such as bark, straw pellets, wet log wood and other inappropriate fuels.
- Under poor operation conditions, an increase of roughly a factor of 2 is expected for pellet combustion, although this value is uncertain due to limited investigations and hence might be underestimated. For downdraft boilers, an increase by a factor of 10 is expected under poor operation conditions. Hence the main advantage of pellet combustion is that very poor operation is assumed to be very rare thanks to the homogeneous fuel and thanks to the continuous fuel feeding. Especially for log wood combustion, the effect of the start-up may significantly increase the average emissions. However, information on this issue is scarce and also uncertain for pellet combustion.
- Wood stoves may achieve similar emissions as pellet combustion or downdraft boilers, if operated ideally. However, ideal operation for wood stoves is expected to be rarely found in practice, as it demands for small batches of small and dry logs, which hence leads to a constant and low heat output by continuous manual feeding of the stove in short periods and assuming an optimised start-up phase, which is often not the case. Since these conditions are often not fulfilled in practice, an increase of almost a factor of 10 is expected for wood stoves under typical operation conditions, thus leading to an estimated value of roughly 150 mg/MJ of solid particles.

- Similar values as for stoves are expected for old-type wood boilers with natural updraft combustion. Hence two stage combustion with forced draft is regarded as a significant improvement. However, the type of operation of log wood boilers in practise strongly depends on the hydraulic integration in the heating system. For conventional house heating, a combination with heat storage tank is usually needed to avoid an operation with sharply throttled air inlet and excessively high emissions.
- For wood stoves, measurements including condensables found in impinger bottles and measurements of particles in diluted flue gases in a dilution tunnel are available as well. A comparison of these data with measurements of solid particles only reveals significantly higher average emission factors. Since the data shown in Figure 6.13 are derived from different investigations and different combustion devices, they do not enable a direct comparison between the different measurement methods. However, the significantly higher (i.e. by a factor of roughly 4) average emission factor reported from measurements in dilution tunnels or data including condensables is in line with the potential of additional particle mass from condensation of highly volatile organic condensables found during poor combustion conditions. The influence of the sampling method is discussed separately in chapter 7, since the data in Figure 6.13 do not allow a direct comparison of the sampling types.

6.7 Influence of ignition method

The ignition method is an important factor for the PM emissions during the start-up phase and often also for the emissions during the whole batch in manually operated wood stoves and boilers. Different methods for the initial ignition and the start-up are applied in practise. Beside fuel size and other parameters, the location of the initial ignition of the wood can be distinguished. In case of wood stoves and closed inset appliances (closed fireplaces) based on a conventional combustion principal with updraft combustion, the following methods have been investigated in an ongoing project in Switzerland [Vock & Jenni 2007]:

- Ignition of the batch of wood from the bottom (traditional method)
- Ignition of the batch of wood from the top end. To enable ignition from the top, a so called “ignition module” was used, which consists of four small dry pieces of wood of app. 3 cm x 3 cm x 20 cm with wax impregnated wood wool on the bottom.

The target of the project is to identify optimum ignition methods for wood stoves and boilers. The ignition shall safely avoid visible smoke at the latest from 15 minutes after ignition and enable good combustion conditions during the whole batch. For all investigated stoves and closed inset appliances, the described ignition principle from the top enabled a reduction of total PM emissions by 50% to 80% in comparison to traditional ignition from the bottom. Furthermore, a smoke free operation was achieved after less than 15 minutes resulting in average PM emissions during the whole batch including start-up in the range of 31 to 53 mg/MJ (70 to 120 mg/m_n³ at 13 Vol.-% O₂) for the investigated stoves instead of app. 87 to 218 mg/MJ (200 to 500 mg/m_n³ at 13 Vol.-% O₂) by traditional ignition from the bottom (Figure 6.14). Consequently, ignition from the top (if applied as described) is regarded as favourable and hence proposed to be applied in practice for conventional wood stoves and closed inset appliances. As a consequence of this investigation, a flyer was developed and distributed, which describes the proposed method of ignition to be applied for conventional updraft combustion and which is available as download [Holzenergie Schweiz 2007 a].

For conventional stoves, the amount of wood used for one batch needs to be adopted to the stove design. For stoves which do not exhibit a separate post combustion chamber, the void space in the upper part of the fuel chamber acts as combustion chamber. In case of utilisation of too much wood at a time, the void space is reduced and hence the remaining residence time is not sufficient for gas mixing and gas phase oxidation. In some cases, also flame quenching may occur. Hence for conventional stoves and closed inlet appliances without separate post combustion chamber, the emissions of unburnt pollutants including soot and organic condensables can strongly increase by using too much wood at a time. Hence beside optimum ignition, the amount of fuel used for one batch is crucial for the total emissions.

For downdraft combustion, the type of ignition can also significantly influence the start-up emissions and the combustion behaviour during the whole batch. The method of optimum ignition is different from those for wood stoves and described for different downdraft principles in detail in a flyer [Holzenergie Schweiz 2007 b]. For downdraft boilers, best results are achieved if the batch of wood is ignited at the location of the outlet of the combustible gases to the combustion chamber. Furthermore, a sufficient amount of small wood pieces to safely ignite the wood and build up a glow bed on the bottom of the fuel bed is important. By application of the proposed ignition method, the risk of fuel bridging and channeling, which can lead to high emissions in downdraft boilers, can be reduced.

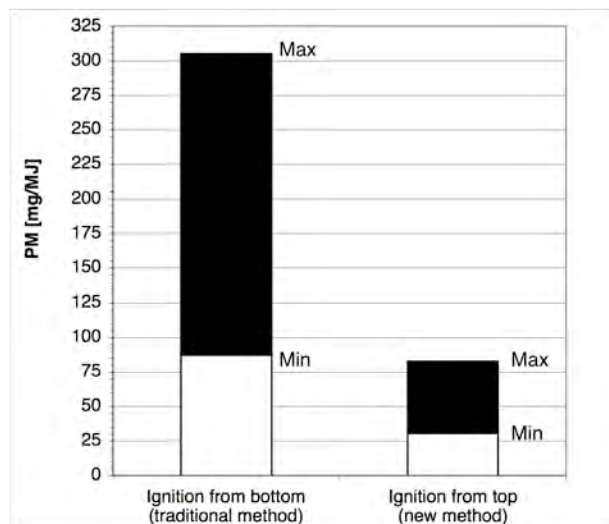


Figure 6.14 Comparison of average PM emissions by ignition from the bottom and from the top applied in different wood stoves. The indicated emission factors describe the emissions during a whole batch including the start-up from the very beginning. Ignition from top is performed by use of an “ignition module” as described above. Data from [Vock & Jenni 2007].

6.8 Automatic biomass combustion plants

Figure 6.15 and Figure 6.16 show the reported emission factors for automatic combustion plants from 70 kW to 500 kW for under stoker and grate boilers respectively. Average emission factors of this category are between 50 mg/MJ and 100 mg/MJ, which is in line with the typical emission limit values valid nowadays (e.g. 150 mg/m³ at 11 or 13 Vol.-% O₂).

However, an investigation of field measurements in Switzerland for a large number of installations revealed a relatively broad range of emissions from 30 mg/MJ up to 350 mg/MJ which demonstrates, that the type of operation is also important for automatic wood combustion plants and that periodic monitoring of such plants is crucial. The same is true for plants from 500 kW to 10 MW as shown in Figure 6.17 and Figure 6.18. However, emission factors of installations in this category strongly depend on the type of flue gas cleaning and thus on the imposed emission limit values. In the category of combustion plants greater than 500 kW, significant changes are expected e.g. in Switzerland², since new emission limit values in this category will make the application of fine particle removal systems necessary in future and thus lead to a significant reduction of PM emissions.

For the comparison of different particle sources it needs to be respected that the presented emission factors are indicated as particle mass concentrations and hence do not respect the health relevance of different particle types. Particles and condensables found from wood burnt under very poor combustion conditions, i.e., in a wood stove with throttled air inlet, contain high concentrations of polycyclic aromatic hydrocarbons and exhibit high cell toxicity and high carcinogenic potential, while particles found from automatic wood combustion at good operation conditions consist mainly of salts and consequently exhibit far lower toxicity and carcinogenicity [Klippel & Nussbaumer 2007].

² 20 mg/m³ at 11 Vol.-% O₂ are valid for plants > 1 MW from 9.1.07 instead of formerly 150 mg/m³,
20 mg/m³ at 13 Vol.-% O₂ are introduced for plants > 500 kW in 2008 instead of formerly 150 mg/m³.

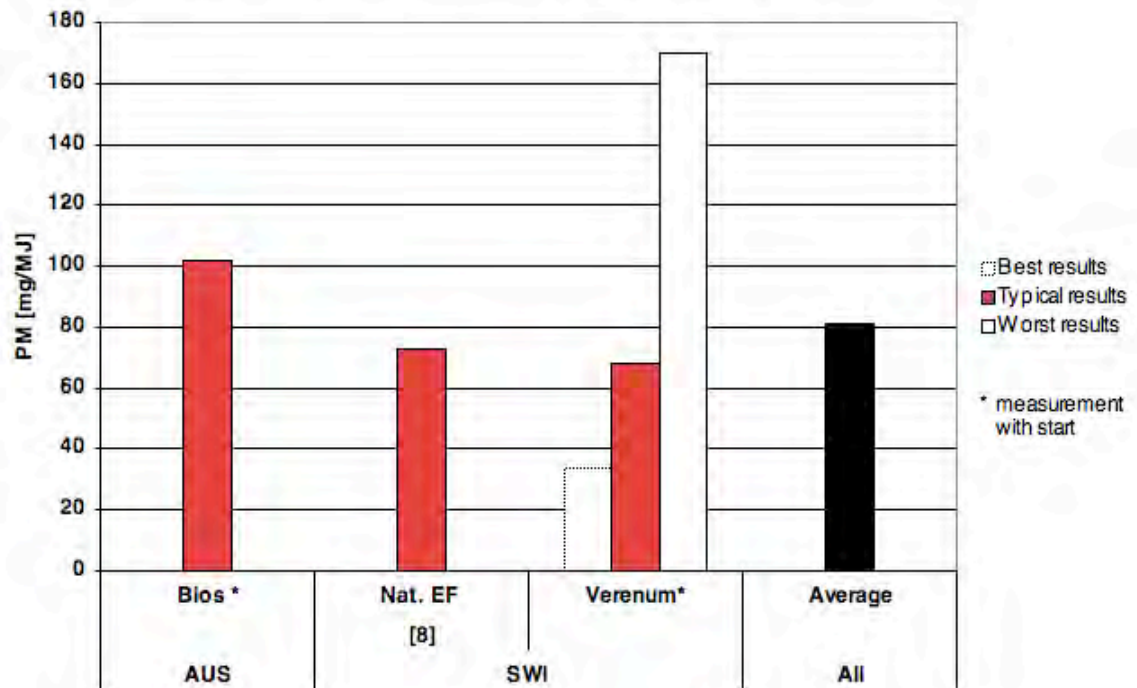


Figure 6.15 Emission factors for under stoker boilers from 70 – 500 kW.

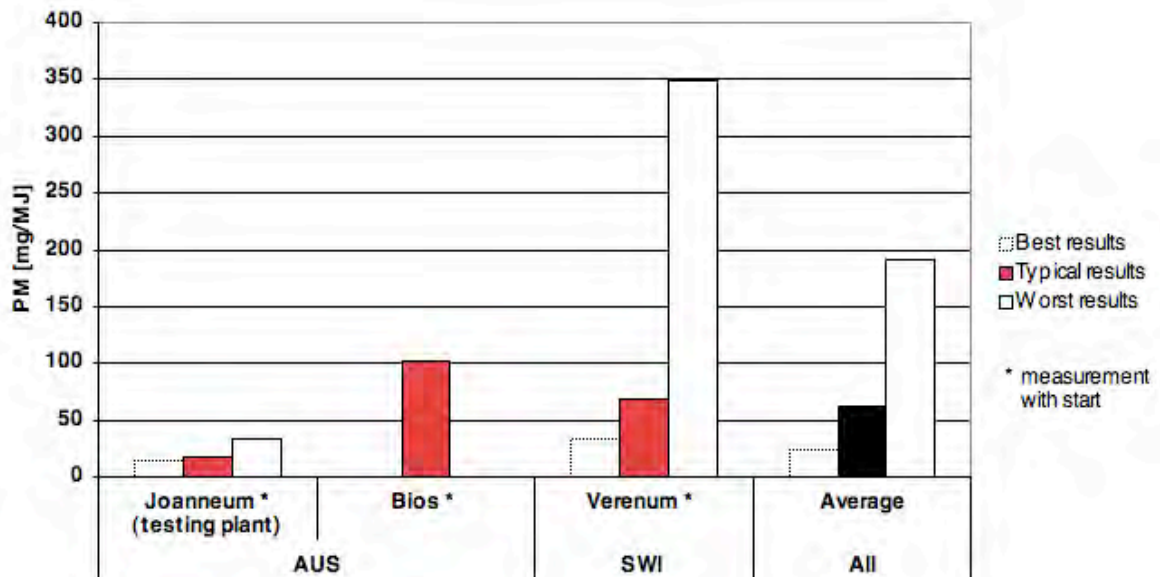


Figure 6.16 Emission factors for grate boilers from 70 – 500 kW.

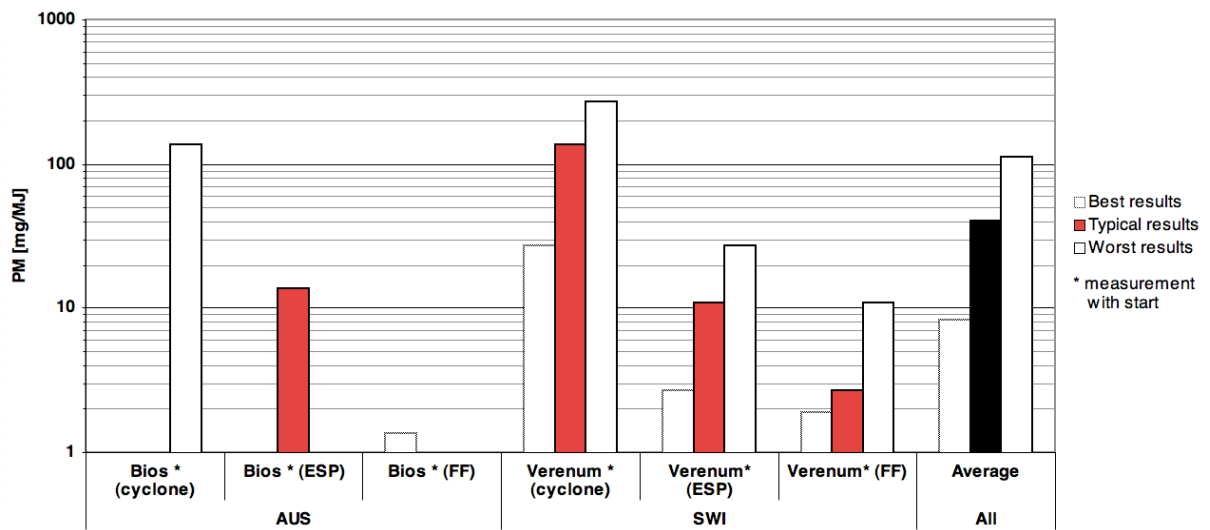


Figure 6.17 Emission factors for under stoker boilers from 500 kW – 10 MW.

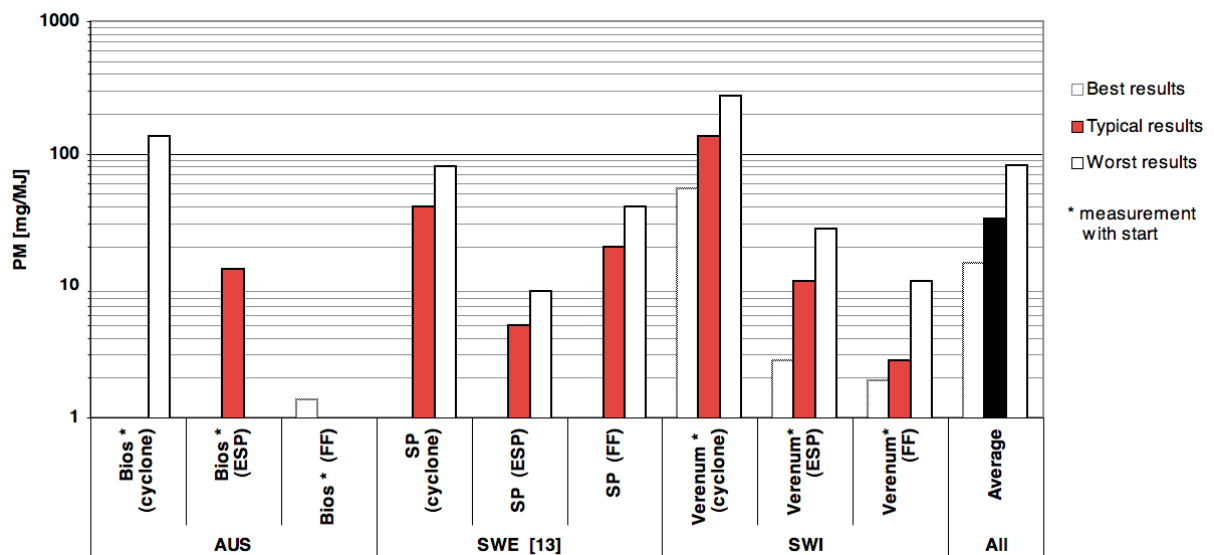


Figure 6.18 Emission factors for grate boilers from 500 kW – 10 MW.

7 Comparison of particle measurements

7.1 Particle sampling: Solid particles, condensables, dilution tunnel

For the emission factors from wood stoves, a limited number of data set is available from Sweden, [Ryde and Johansson, 2007], where parallel measurements were performed by sampling method a resulting in solid particles (SP) and sampling method c resulting in particles found on the filter in the dilution tunnel (DT) as described in chapter 4.2. In addition, data are available from measurements on wood stoves in Switzerland with separate sampling of solid particles and subsequent condensable matter thus resulting in SP according to method a and SPC according to method b.

Figure 7.1 shows that the PM emission factor found in the dilution tunnel is significantly higher than the solid particle emissions detected in the chimney. The same is true for the data found including condensables in impingers.

Figure 7.2 illustrates the ratio of DT/SP in case of dilution tunnel and of SPC/SP in case of condensables found in impingers. In one single case (Verenum stove 3) which corresponds to a high combustion quality resulting in low total PM emissions, the ratio SPC/SP is only slightly above 1 (≤ 1.1), while in all other cases with poor combustion conditions (throttled air supply), the reported ratios DT/SP are between 2.5 and close to 10 (data from Sweden) and the ratios of SPC/SP are between 3 to 6 (Switzerland).

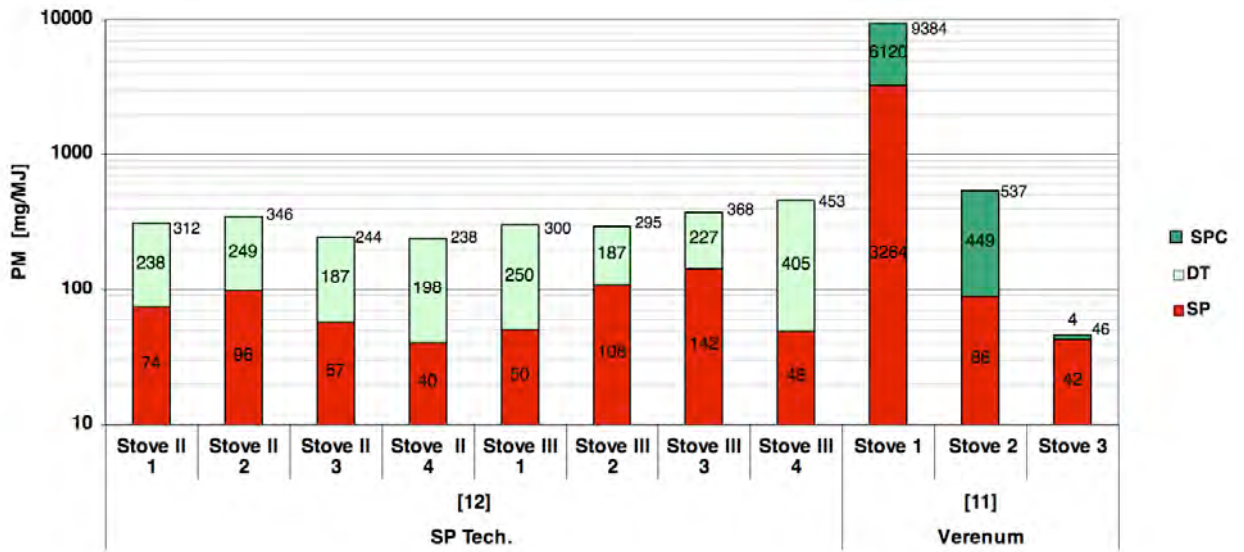


Figure 7.1 Comparison of PM emission factors on solid particles (SP), particles in dilution tunnel (DT), and solid particles plus condensables from impinger (SPC) for wood stoves.

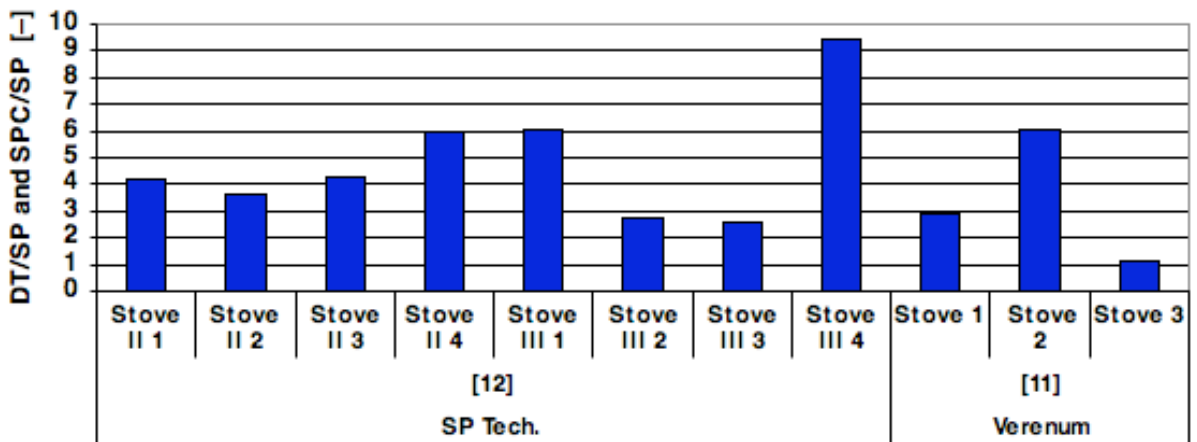


Figure 7.2 Ratio DT/SP and SPC/SP for wood stoves acc. to Figure 7.1.

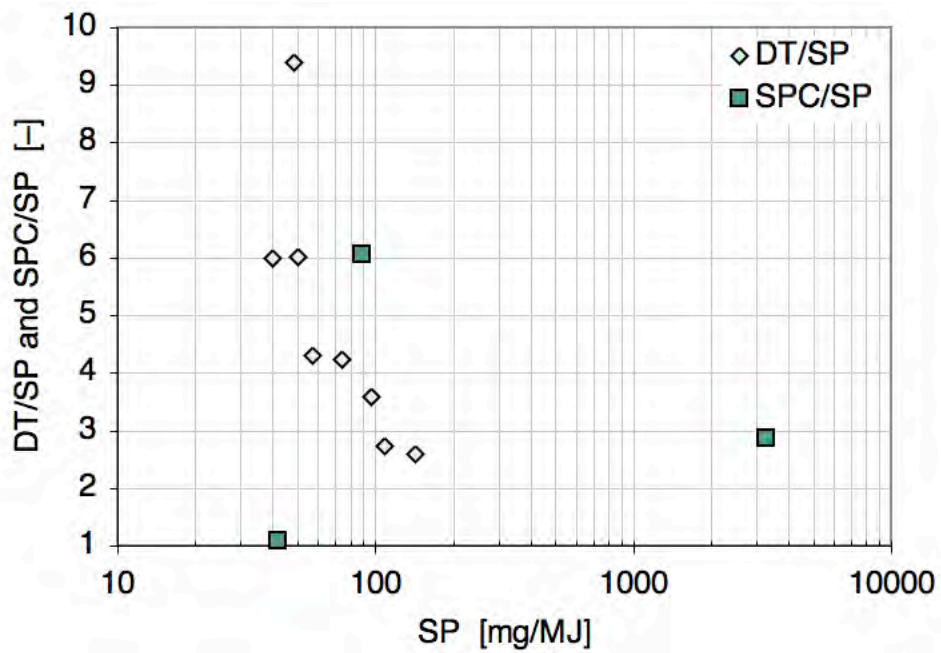


Figure 7.3 Ratio DT/SP and SPC/SP for wood stoves as function of SP.

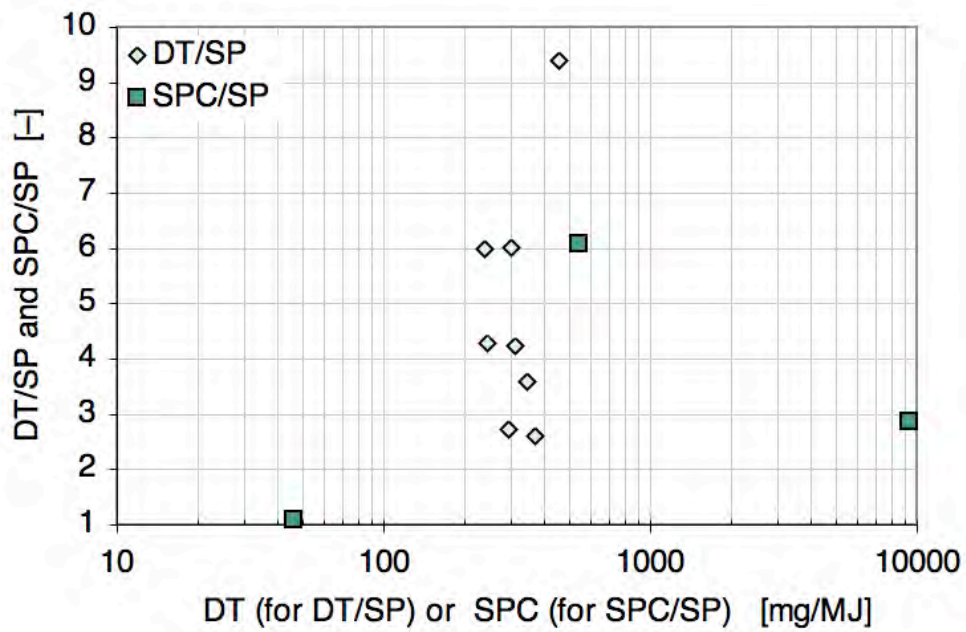


Figure 7.4 Ratio DT/SP and SPC/SP for wood stoves as function of SPC and DT respectively.

7.2 Particle size measurements

Figure 7.5 shows the distribution of equipment used for particle size analysis by 12 institutions which are involved in this work. Figure 7.6 describes the individual ranking of the usefulness of different equipment, while Figure 7.7 shows the average ranking.

- Almost all institutes use low-pressure cascade impactors and assess this measurement as highly useful.
- Scanning mobility particle sizer (SMPS) is used by 50% of all participants and judged with a top ranking.
- Fast mobility particle sizer (FMPS) is in use in one institute, while a ranking is not yet available.
- Electric low-pressure impactor (ELPI) is used by 50% of all institutes and exhibits a heterogeneous ranking.
- Optical particle counter (OPC) is used by 25% and exhibits a top ranking.
- Opacity meter is not in use any more by the participants, but received a low ranking due to earlier experiences.
- Aerodynamic particle sizer (APS) is used by 2 institutes and is judged with a high ranking.
- Tapered element oscillating micro-balance TEOM is used by 40% and exhibits a high ranking.
- One institute indicates to use cyclone, where no ranking was available.

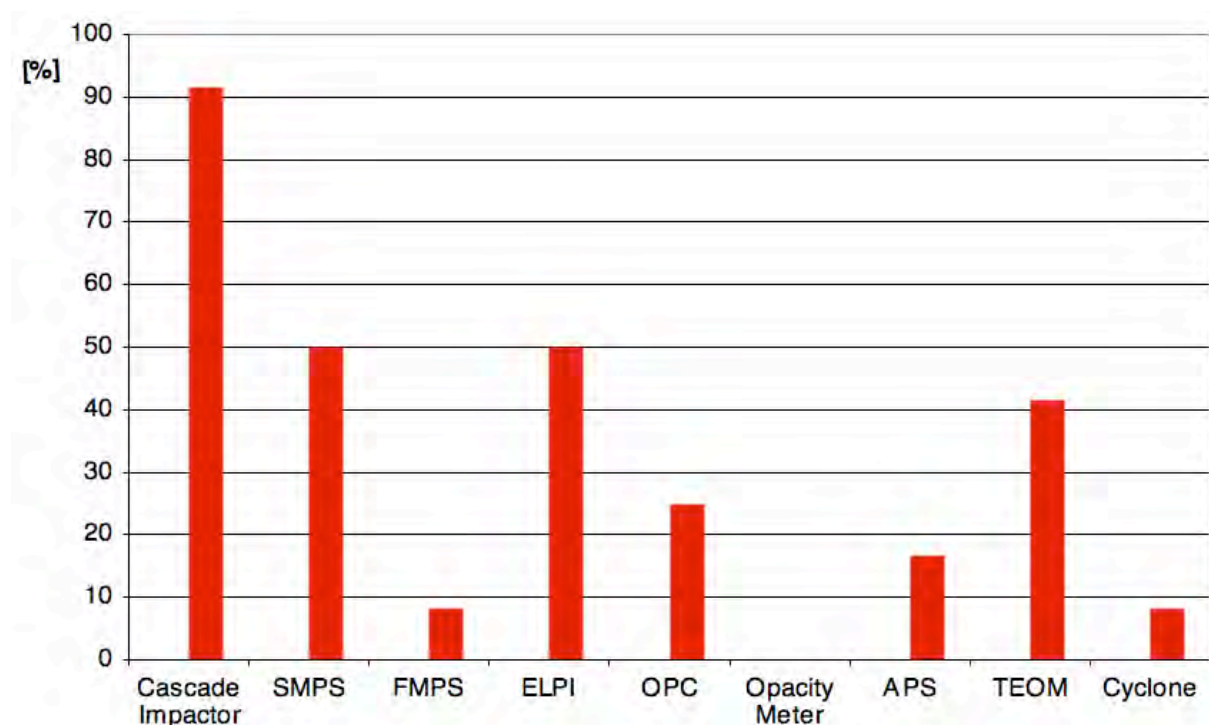


Figure 7.5 Percentage of application of particle size measurements in 12 participating institutions. For cascade impactors, Anderson, Berner, Dekati, and Kalman are summarized.

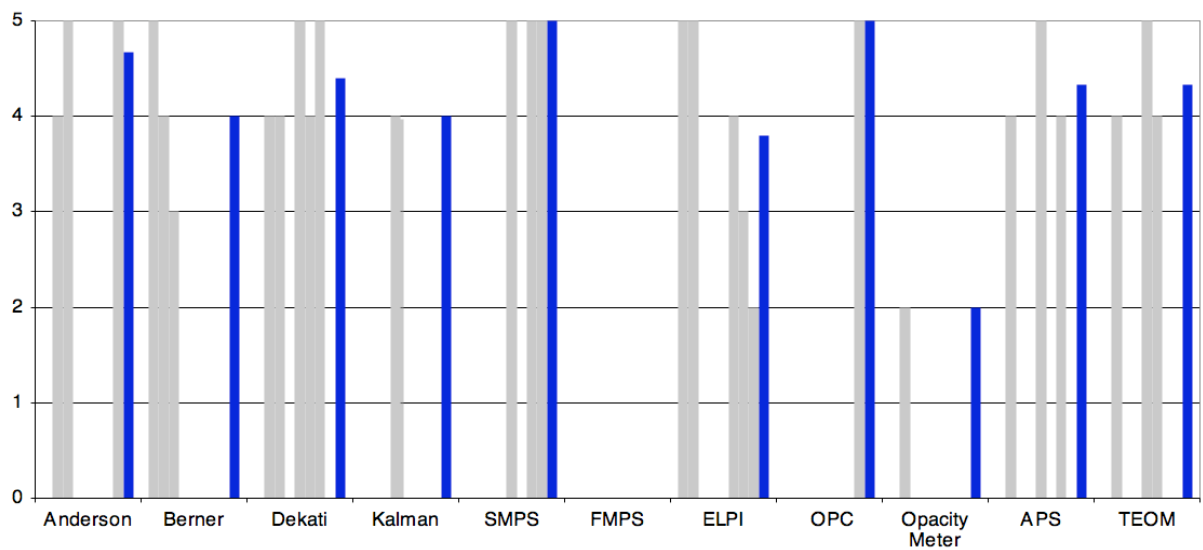


Figure 7.6 Ranking of usefulness of different particle size measurements. Grey = individual ranking, blue = average. For FMPS there is no ranking available.

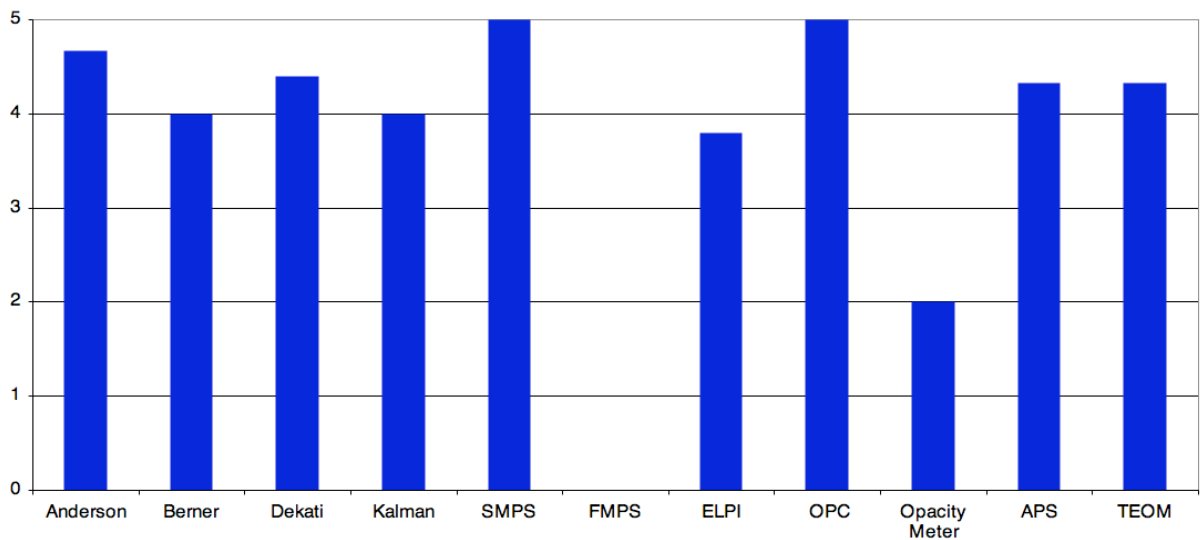


Figure 7.7 Average ranking of usefulness of different particle size measurements acc. to Figure 7.6. 5 = Maximum ranking. For FMPS there is no ranking available.

8 Conclusions

Data on emission factors of residential wood combustion have been collected from 17 institutions in seven IEA countries. Huge ranges of emission factors are reported for residential wood combustion, while emission factors of medium and large scale applications mainly depend on particle removal equipment, related to national or local emission limit values. Consequently, conclusions from the present study mainly focus on residential applications

- The reported emission factors from manual wood combustion devices exhibit huge ranges from less than 20 mg/MJ under ideal conditions up to more than 5 000 mg/MJ under poor conditions (data refer to end energy indicated as lower heating value). Even national emission factors vary from less than 100 mg/MJ (measured as solid particles in the chimney) up to almost 2 000 mg/MJ (measured in a dilution tunnel).
- For wood stoves, huge ranges are found due to different operation conditions. Consequently, high priority should be given to avoid inappropriate operation of manual wood combustion appliances. Excessive PM emissions are found during smoldering conditions at reduced load and at throttled air supply. This type of operation is not recommended, but nevertheless seems to be relevant in practical operation in many countries. In many cases, the start-up phase is responsible for more than 50% of the total PM emissions of a whole batch. Hence measures for optimisation of the start-up are very important. For conventional wood stoves and closed inset appliances, a comparison of different ignition methods in Switzerland showed, that ignition from the top enables a reduction of 50% to 80% of the PM emissions in comparison to ignition of the whole batch from the bottom. Consequently, this method is being proposed for application in practice.
- For wood boilers, excessive PM emissions are reported for boilers operated without heat storage tank. This is in line with the observation found in stoves, since boiler operation for house heating applied without heat storage tank often leads to part load combustion. Hence, heat storage tanks are mandatory for log wood boilers in Switzerland, except if the boiler does achieve the emission limit values at constant heat demand of maximum 30% of the nominal load, which is possible for pellet boilers but not realistic for log wood boilers. To avoid poor operation of log wood boilers, similar regulations are recommended, which might not disable new technical solutions in future. In Sweden, emission limits imply heat storage tanks for new installations, in practice it is mandatory today, but in the future other technical solutions might fulfil the emission regulations. For log wood boilers with downdraft principle, optimised ignition can reduce the risk of bridging and channelling in the fuel bed, which is a current reason for high emissions in such boilers.
- For residential wood boilers, the type of combustion is also significantly influencing the PM emission. Modern boilers with forced downdraft combustion and electronic combustion control devices enable low particle emissions under appropriate combustion conditions, while old-type boilers with updraft combustion exhibit higher emissions under similar conditions. However, the influence of operation mode cannot be evaluated in detail based on the reported data.
- For pellet boilers and stoves, typical particle emissions of around 30 mg/MJ are reported with a relatively narrow variation from 10 mg/MJ to 50 mg/MJ. Hence, the total PM emissions under typical operation conditions are expected to be far lower than for manual wood stoves. The problem of variations between ideal operation and inappropriate operation are certainly less emphasized than in manual boilers, although data on poorly operated pellet combustion are scarce and hence the

upper range from pellet combustion is uncertain. It should be noted that the market for pellets is growing and the production of second grade quality pellets with higher ash content will increase. The use of these pellets in small-scale equipment without secondary particle reduction will result in higher emissions. Thus, good quality pellets should be reserved for domestic scale applications.

- For automatic combustion plants, the emission factors for plants without electrostatic precipitator (ESP) or fabric filter (FF) are relatively high, i.e. typically between 50 to 100 mg/MJ, which, under good combustion conditions, is attributed to high emissions of inorganic particles. Hence clean gas emissions strongly depend on the type of flue gas cleaning applied, which depends on national or local emission standards. In many European countries, emission limit values for such applications have recently been sharpened and hence the situation of typical PM emissions will change in many countries in the future, since particle removal enable clean gas emissions of typically smaller than 30 mg/MJ (simple ESP) or smaller than 10 mg/MJ (improved ESP or FF).
- For the comparison of different data, the sampling and measurement procedure needs to be considered. In the present study, three types of data are distinguished: Filterable, solid particles (SP) collected on heated filters, solid particles plus condensables found by liquid quenching at room temperature (SPC), and particulate matter sampled in cold, diluted flue gas in a dilution tunnel (DT). A comparison between SP and SPC shows that the mass of condensables may significantly exceed the mass of solid particles during poor combustion conditions in wood stoves. A comparison between results from a dilution tunnel with sampling in the chimney reveals significantly higher concentrations in the diluted flue gas and thus shows, that condensables are partially or quantitatively found as filterable material after dilution of the flue gas with cold air. Consequently, PM immission inventories based on emission factors of solid particles may significantly underestimate the contribution of biomass to PM in the ambient air. This is in line with results from immission measurements, where a higher contribution from wood combustion is found than expected from emission factors used in Switzerland [Prévot et al. 2006]. In addition, data reported from countries with regulations on solid particles as e.g. Germany, Austria, and Switzerland, cannot be directly compared with data reported from countries using dilution tunnels as e.g. Norway. Consequently, the type of measurement is indicated in all results presented in this survey and it is recommended to clearly indicate the type of measurement for future emission inventories.
- Since condensables from wood combustion have been identified as highly toxic and since they can significantly contribute to total PM in the ambient air, it is recommended to use emission data including condensable PM in immission studies (SPC or DT in this report). Furthermore, since organic condensables are highly toxic, while solid particle can exhibit low toxicity (in case of salts) or high toxicity (in case of particles from incomplete combustion), a separate measurement of both parameters is regarded as advantageous. However, measurement of solid particles only is less equipment and time consuming and still gives a performance value for PM emissions for comparison of different combustion appliances.
- A survey on equipment used for particle size measurement reveals that nowadays low-pressure cascade impactors are used in almost all laboratories dealing with particle measurement. In addition, half of the participating institutions use scanning mobility particle sizer (SMPS) and/or electric low-pressure impactor (ELPI). Further, optical particle counter (OPC), aerodynamic particle sizer (APS), and tapered element oscillating micro-balance (TEOM) are currently used.

9 References

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