BIOMASS COMBUSTION IN EUROPE OVERVIEW ON TECHNOLOGIES AND REGULATIONS

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NEW YORK STATE
ENERGY RESEARCH AND
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Final Report

Prepared for the
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1 Summary

Biomass combustion in Europe is widely applied for residential heating in stoves and boilers, district heating in automatic combustion plants, and combined heat and power production in industrial scale boilers. This report gives an introduction to the combustion fundamentals, an overview of combustion technologies applied in Europe today, an assessment on particulate matter emissions smaller than 10 microns (PM_{10}), and an overview of regulations and norms on emissions from wood combustion devices. For small-scale applications, mainly log wood is used as fuel today with an increasing interest in wood pellets, while for medium-scale applications, wood chips are most common. The technologies of combustion systems are presented, and their relevance to pollutant emissions is discussed. For this purpose, the characteristics of wood as a fuel and the reactions during wood combustion are presented. It is shown that biomass combustion is related to relatively high pollutant formation due to the following mechanisms:

1. An incomplete combustion can lead to high emissions of uncombusted pollutants, i.e., CO, VOC, PAH, soot, and condensable organic matter. A significant reduction of uncombusted pollutants can be achieved by two-stage combustion with gasification of the wood with primary air and a subsequent gas phase oxidation with secondary air. This technology is applied to modern type boilers by application of the downdraft principle, while wood stoves are mostly based on conventional updraft combustion. In addition, manually-operated wood combustion strongly influences the emissions in practice. Non-ideal operation can lead to an increase of uncombusted pollutants, including PM, by more than one, or in some cases more than two orders of magnitude. Solid particles and condensables from incomplete wood combustion exhibit a high health risk. Investigations of such particles revealed a far higher health relevance (i.e., cell toxicity and chromosome aberration) than Diesel soot, while inorganic particles from almost complete combustion of wood exhibit a significantly lower health impact than Diesel soot.
2. Inorganic particles and NO_X are formed as a result of fuel constituents (N, K, Cl, Ca, Na, Mg, S and other elements). Hence biomass combustion exhibits relatively high emissions of NO_X and particles (which under good combustion consist mainly of inorganic matter from ash constituents). Air staging and fuel staging offer a certain potential to reduce NO_X, while staged combustion by low excess air and reduced temperatures in the primary zone enables a reduction of inorganic particles. Furthermore, particle separation and selective NO_X reduction are available as secondary measures for pollutant reduction.
3. Contaminants such as heavy metals and chlorine can lead to additional airborne emissions.

Based on a two-stage combustion principle, and with application of electronic combustion control devices, modern log wood boilers can achieve high combustion efficiencies (i.e., up to more than 90% based on lower heating value), high overall system efficiency (i.e., more than 80%), and low PM emissions (i.e., smaller than 30 mg/MJ or 0.070 lb/MMBTU). However, to ensure good operation conditions for residential heating applications, a heat accumulation tank is needed for log wood boilers to avoid part-load operation. Properly operated modern log wood boilers allow significant fuel savings in comparison to old-type boilers, which do not exhibit a two-stage combustion design and electronic combustion control and often achieve efficiencies of less than 60% or even less than 50%. Furthermore, a reduction of PM emission of more than one order of magnitude can be achieved in comparison to poorly designed and operated log wood boilers. Therefore, replacing old-type log wood boilers operated without a heat storage (often in use in the United States for outdoor wood boilers (OWB)) by modern log wood boilers allows significant reduction of PM emissions and hence can strongly assist to avoid the excess of ambient air quality limits. For new wood heating appliances, the implementation of well designed combustion principles, as well as the application of heat accumulation tanks, is essential to avoid an increase of PM emissions.

Keywords: Wood combustion, pollutant formation, pollutant reduction, particulate matter, regulations

2 Introduction

2.1 Motivation

Biomass is widely applied as a renewable energy source for heat and power production and will become more important in the next decades due to declining fossil fuels. While sustainable use of biomass can be regarded as partly CO_2 free, biomass combustion is an important source of air emissions, especially inhalable particulate matter smaller than 10 microns (PM_{10}) in the ambient air, polycyclic aromatic hydrocarbons (PAH), volatile organic compounds (VOC), nitric oxide emissions (NO_X), and potentially polychlorinated dibenzo-*p*-dioxins and furans (PCDD/F). Since PM 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, new technologies with reduced PM emissions are of interest:

- Improved wood boilers include a two-stage combustion principle and an injection of secondary air prior to a hot combustion chamber. Furthermore, electronic combustion control should be applied to ensure optimum operation in practice, and forced ventilation should be applied to enable good mixing and less dependence on the ambient climate conditions such as air temperature and wind. In addition, wood boilers used for house heating should be equipped with a heat accumulation tank to avoid part-load operation with increased emissions. This type of boiler is available as state-of-the-art technology in Europe and can be widely implemented.
- Similar to boilers, wood stoves might be developed, which exhibit an improved combustion principle with a hot combustion chamber and good mixing of combustion air with combustible gases. However, stove design for visible flames and operation without a ventilator exhibits limited possibilities of application of improved combustion principles. For stoves, design principles should be developed that avoid improper operation of the stove. Therefore, overfilling of the combustion chamber and the possibility to reduce the air inlet, resulting in smoldering conditions, should be avoided. Since wood stoves do not safely achieve these requirements, further development is needed.
- In addition to the implementation of improved technologies for new heating appliances, it is essential to ensure ideal operation of existing wood stoves and boilers. This can be achieved to some extent by providing information and measures to the consumers.
- Besides technical improvements for residential wood heating appliances, it is also essential to prohibit burning of wood and other biomass in open fires, as well as private waste incineration. These types of combustion are related to excessively high air pollution without energy use.
- As an alternative for log wood, wood pellets can be used for residential heating. Thanks to constant fuel properties and small size, automatic feeding can be applied, which allows improved combustion conditions. However, for pellet combustion, optimum operation needs to be ensured by combustion control, which avoids smoldering conditions especially during start-up and shut-down.

- As an additional measure, technologies for flue gas cleaning for small-scale applications are being developed and offers a certain potential for pollutant reduction for existing and new wood heating appliances.
- Finally, wood fuel can be used in automatic biomass combustion plants, which can be equipped with flue gas cleaning such as electrostatic precipitators or fabric filters. If well designed and operated, automatic combustion plants for wood fuels achieve almost complete combustion, which safely avoid uncombusted particles. Inorganic particles can be precipitated by filters thus allowing low PM emissions.

Improvements in different sectors should be aimed at achieving a significant reduction of PM emissions from wood combustion. Due to the steep increase in PM emissions and the high health risk of particles and condensables released during incomplete combustion, the main goal is to safely avoid the use of wood stoves and boilers operated at such conditions. Visible smoke and noticeable odors are clear indicators of high and toxic emissions, which need to be safely avoided, or be limited to short periods during start-up (i.e., certainly less than 15 minutes). Beside development of improved technologies, regulations are important, which allow a useful evaluation of PM emissions.

In addition to the implementation of technical measures to reduce PM from wood combustion, there is a need to improve information on the contribution of biomass combustion to the total PM in the ambient air and its relevance for the environment and the health. This is true for Europe, where investigations on PM in the ambient air reveal a significant contribution of wood combustion. For example, more than 80% of the soot in the alpine valleys in Switzerland close to transit highways during winter originates from wood combustion [Prévot et al. 2006]. However, there is a lack of systematic information on the formation of PM under different conditions in Europe and in the United States.

In the United States there is a need to improve the information on PM. The NARSTO Emission Inventory Assessment Team claims that the highest priority needs for improving emission inventories are [NARSTO 2005]:

- Size-aggregated, speciated emissions of fine particles and their precursors, including black and organic carbon emissions
- Speciated, spatially and temporally resolved organic emissions from biogenic sources
- Emissions from open biomass burning, including agricultural and forest prescribed burning, wildfires, and residential backyard burning
- Residential wood combustion in woodstoves and fireplaces

In addition, the Northeast States for Coordinated Air Use Management identifies in their assessment of carbonaceous $PM_{2.5}$ for New York and the region seven major sources for emissions [NESCAUM and MJB Associates 2008]: Five mobile source sectors (nonroad equipment, heavy-duty trucks, light-duty vehicles,airports, and marine ports) and two stationary source sectors (residential fuel combustion and commercial cooking).

There is a specific need for improved information on emissions from residential wood combustion as well as from open biomass burning and its relevance to PM in the ambient air. Consequently, the conversion of emissions released from the stack to the ambient is an important issue, too, since secondary organic aerosols (SOA), induced by photochemical oxidation of volatile and semivolatile organic compounds, can significantly contribute to the total PM concentration in the ambient air (e.g. [Shrivastava et al. 2006, Lipsky & Robinson 2006, Robinson 2007, Robinson et al. 2007]).

2.2 Objectives

The objective of the study is to give an introduction on combustion fundamentals for wood fuels and an overview of state-of-the-art technologies for wood combustion in Europe. The assessment of technologies and applications will focus on efficiency and on air pollution with special attention to particulate matter in the ambient air resulting from wood fuel applications. Hence, testing procedures for PM emissions in Europe will be described and compared with testing according to US standards. Ongoing R&D activities in Europe shall be discussed and recommendations for future developments in the State of New York to reduce PM from wood combustion will be provided.

2.3 Conversion of emission factors

Gaseous emissions are usually measured in volume concentrations such as Vol.-% or Vol.-ppm, while gravimetric measurements of particles (PM) result in mass concentrations such as mg/m^3. Gravimetric PM emissions in mg/m^3 can be compared to PM concentrations in the ambient air, which are also measured as mass concentrations and usually given in μg/m^3. For specific gas compounds such as CO or NO_2, measurements in volume concentrations can be directly converted to mass concentrations. To allow a comparison of emission factors achieved at different excess air ratios, a conversion to a reference oxygen concentration is performed. Consequently, European norms and regulations often use mass concentrations calculated at a reference O_2 for the definition of emission limit values. In the present report, data in mg/m^3 at 11 vol.-% O_2 or 13 Vol.-% O_2 (dry volume at 0°C and 1013 mbar) are used (as valid examples for the Swiss Ordinance of Air Pollution Control). However, for the comparison of emission factors a calculation on energy basis is more favorable, as it allows for a comparison with other fuels. For this purpose, mass concentrations are converted to mg/MJ with reference to the lower heating value. In the USA, emission factors are also commonly used in g/MMBTU and lb/MMBTU, where MM stands for 1 million. Hence, the following conversion can be applied:

$$\boxed{1\ \text{mg/MJ} = 1.055\ \text{g/MMBTU} = 0.00232\ \text{lb/MMBTU}}$$

Figures on conversion factors in the present report are given in mg/MJ and can easily be read for g/MMBTU by multiplying with 1.055. This is a conversion, which can be neglected for a generic interpretation. For data in lb/MMBTU, an indicative second axis is added in the figures and data are converted in the text.

3 Wood combustion technology

3.1 Overview

There are three basic technologies for an initial thermochemical conversion of biomass: pyrolysis, gasification, and combustion. Among these, combustion is the most proven technology for heat and power production. The technologies are described in [Nussbaumer 2003] and summarized in the present chapter.

Pyrolysis is of interest as an initial process for liquid biofuel production. However, pyrolysis is in an early stage of development, and the potential advantages over combustion applications are uncertain.

Gasification is of interest for future applications due to two advantages: higher electric efficiencies are possible by gasification, especially if the producer gas is used for combined cycle applications, and gasification allows an application with very low airborne emissions. PM emissions can be significantly reduced in comparison to conventional combustion, since highly efficient particle removal in the raw gas needs to be applied to protect the gas turbine and/or the turbo charger. Furthermore, an almost complete combustion of the producer gas in the gas turbine combustion chamber is reached, thus resulting in negligible organic emissions such as VOC and organic condensables. Hence, clean gas emissions from gasification plants can be very low. Although such applications should be considered in the future as promising alternatives, today, the majority of the wood fuel is used in combustion applications, which are available as proven technology.

Biomass combustion systems are available from a few kW up to more than 100 MW. Typical applications in Europe cover the following size ranges:

1. Manual wood stoves are most commonly used from 5 kW to 15 kW. However, due to the batch-operation, the instantaneouos combustion heat performance can also exceed 50 kW for a short period of time in applications as e.g. tile stoves which exhibit a heat accumulation in the high mass of the stove.
2. Manual log wood boilers are most commonly used from 20 kW to 70 kW. For typical house heating, heat accumulation tanks with a few 1000 liter of water are used to increase comort and avoid part-load operation of the boilers at low efficiency and high emissions.
3. Pellet stoves and boilers for house heating are most common from 15 kW to 70 kW (for boilers). However, larger applications of more than 1 MW for wood pellets are also used e.g. in cases, where the limited space does not allow the use of wood chips.
4. Wood chips boilers are most often used from 200 kW to 10 MW heat output, although in some cases wood chips are also used from 20 kW and up to more than 100 MW. For applications greater than 1 MW, grate boilers are most common, while for smaller plants, under stoker boilers are in use in case of relatively high quality wood chips. Applications with heat output of more than 10 MW to 20 MW are often combined with steam production for combined heat and power production.

The efficiency for heat production is considerably high, and heat from biomass is economically feasible in many applications. Commercial power production is based on steam cycles. The specific cost and the efficiency of steam plants are only adequate at large-scale applications. Hence, co-combustion of biomass with coal is promising, as it combines high efficiency with reasonable transport distances for the biomass.

However, biomass combustion is often related to significant pollutant formation and needs to be improved. To develop measures for emission reduction, the specific fuel properties need to be considered. Pollutant formation occurs due to three reasons:

1. Incomplete combustion can lead to high emissions of uncombusted pollutants such as CO, soot, organic condensables ("tar"), and polycyclic aromatic hydrocarbons (PAH).
2. Pollutants such as NO_X and particles are formed as a result of natural fuel constituents such as N, K, Cl, Ca, Na, Mg, P, and S.
3. Biofuels can be carriers of additional contaminants such as heavy metals or chlorine, which can lead to high emissions of heavy metals, HCl, and potentially highly toxic polychlorinated dibenzo-*p*-dioxins and furans (PCDD/F).

Biomass combustion exhibits relatively high emissions of NO_X and submicron particles. Air staging and fuel staging can be applied as primary measures for NO_X reduction that offer a potential of 50% to 80% reduction. For further reduction, secondary measures such as selective catalytic and selective non-catalytic reduction (SCR, SNCR) can be applied. However, SNCR can lead to significant undesired side-products that need to be carefully avoided.

For particle reduction, the main goal is to achieve an almost complete combustion that safely avoids soot, organic particles and droplets, and volatile organic compounds in the flue gas. Primary measures to reduce inorganic PM by staged combustion with an initial gasification stage offer a certain reduction potential. For this purpose, a new approach with extensively reduced primary air is under investigation. Furthermore, optimized plant operation is needed to guarantee low emissions and high efficiency under real-world conditions. Nevertheless, secondary measures for PM removal are needed for medium and large-scale applications. In addition, there is also an interest in secondary measures for future applications in residential wood combustion.

3.2 Biomass fuels

Combustion can be applied to biomass feedstock with water contents up to 60%. Fuel constituents beside C, H, and O are undesired, since they are related to pollutant and deposit formation, corrosion, and ash. The most relevant constituents in native biomass are nitrogen as a source of NO_X, and ash components (e.g. K and Cl as a source of KCl) that lead to particulate emissions. Native wood is usually the most favorable bio fuel for combustion due to its low content of ash and nitrogen. Herbaceous biomass such as straw, miscanthus, and switch grass have higher contents of N, S, K, and Cl, which lead to higher emissions of NO_X and particulates, increased ash, corrosion, and deposits. While wood is well-suited for household heating as well as for larger plants, herbaceous biomass is reserved for larger plants. The same is true for urban waste wood and demolition wood. The combustion of such contaminated biomass should be strictly limited to combustion plants with efficient flue gas cleaning for the abatement of toxic pollutants such as heavy metals and chlorine compounds.

The driving force for biomass combustion for energy purposes is either the CO_2 neutrality of sustainable cultivated biomass or the use of biomass residues and waste. Large potentials of both native biomass and biomass wastes are still available and allow a relevant increase of sustainable bio energy use in the future. Combustion is the most important technology available today for biomass use. Improvements in efficiency, emissions, and cost are needed for further exploitation. In addition, alternatives such as gasification and combinations of different processes such as gasification as fuel pre-treatment for co-combustion need to be considered.

3.3 Environmental impact of biomass combustion

Biomass combustion exhibits relatively high emissions of NO_X and particulates in comparison to the combustion of natural gas or light fuel oil. Hence, biomass combustion contributes significantly to particulate matter (PM), ozone, and NO_2 in the ambient air. For wood combustion, a life cycle assessment (LCA) indicates that 38.6% of the environmental impact of a modern automatic wood furnace is attributed to NO_X, 36.5% to PM 10, only 2% to CO_2 and 22.9% to all other pollutants (Table 3.1). The LCA for wood, light fuel oil, and natural gas also show that the environmental impact of wood is higher than that for natural gas for a standard valuation of the greenhouse effect. Hence, improvements in the wood chain are necessary. However, it is also evident that the conclusions of the LCA strongly depend on the valuation of the greenhouse effect, since the ranking changes significantly as a result of the different CO_2 impacts of the three fuels.

On the other hand, in case of poor combustion conditions in manually operated wood stoves or boilers, PM emissions can be higher than assumed in the cited LCA by a factor of 10 thus leading to a far higher environmental impact than described here [Klippel and Nussbaumer 2007 (a) and (b)]. In addition, at excessively high emissions of unburnt hydrocarbons including methane, even the greenhouse gas effect can be higher than from light fuel oil or natural gas due to the higher impact of methane [Johansson et al. 2004]. Hence wood combustion can only be assessed as being environmentally friendly in case of low airborne emissions.

Table 3.1 Environmental Impact Points (EIP) according to the Ecological Scarcity Method for heating with wood chips (base case for greenhouse effect), data from [Kessler et al. 2000]

	[EIP/GJ]	[%]
NO_X	13 030	38.6%
PM 10	12 600	36.5%
CO_2	670	2.0%
SO_X, NH_3, CH_4, NMVOC, primary energy, residues, and others	8 200	22.9%
Total	34 500	100%

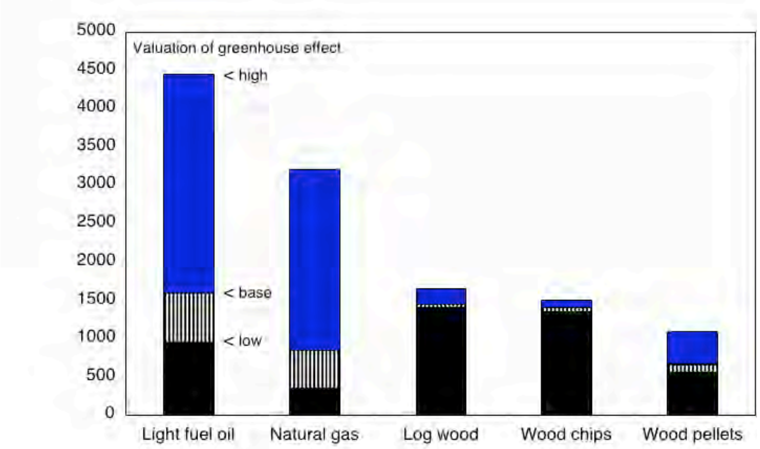

Figure 3.1 Environmental impact points (EIP) for different valuations of the greenhouse effect. Data from Kessler et al. 2000, except wood pellets, own calculations [2003].

3.4 Fundamentals

Biomass combustion is a complex process that consists of consecutive heterogeneous and homogeneous reactions. The main process steps are *drying, devolatilization, gasification, char combustion, and gas phase oxidation*. The time used for each reaction depends on the fuel size, properties, temperature, and combustion conditions. Batch combustion of a small particle shows a distinct separation between a volatile and a char combustion phase with time (Fehler! Verweisquelle konnte nicht gefunden werden.). For the design of combustion appliances, the high content of volatiles (80% to 85%) needs to be respected. For large particles, the phases overlap to a certain extent. Nevertheless, even for log wood furnaces, a certain separation of distinct combustion regimes with time can be found.

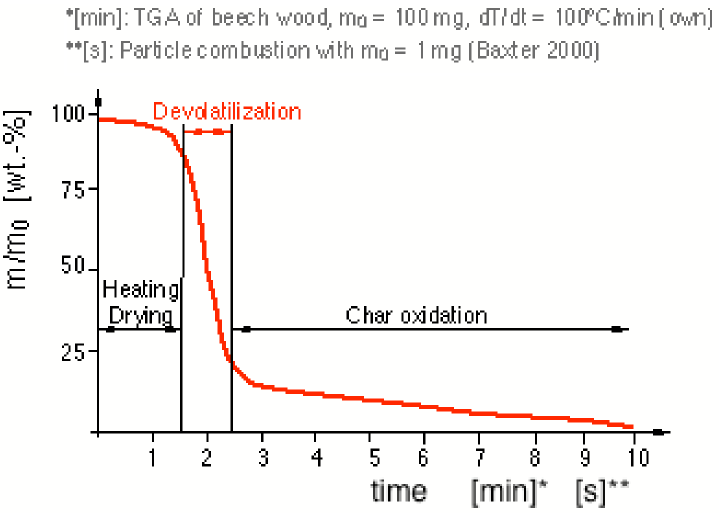

Figure 3.2 Mass loss as function of time during combustion of wood

Since automatic combustion systems are operated continuously, the consecutive reactions occur simultaneously at different places in the furnace (e.g., in different sections on and above a grate). Therefore, the zones for different steps during combustion can be optimized by furnace design. A distinct separation of different steps can be advantageous with respect to pollutant formation.

The main combustion parameter is the *excess air ratio (lambda; λ)* that describes the ratio between the locally available and the stoichiometric amount of combustion air. For typical biomass, the combustion reaction can then be described by the following equation, if fuel constituents such as N, K, Cl etc. are neglected:

$$CH_{1.44}O_{0.66} + \lambda\ 1.03\ (O_2\ + 3.76\ N_2) \rightarrow \text{Intermediates } (C, CO, H_2, CO_2, C_mH_n\ \text{etc.})$$

$$\rightarrow CO_2 + 0.72\ H_2O + (\lambda - 1)\ O_2 + \lambda\ 3.87\ N_2\ \ -439\ \text{kJ/kmol}$$

where $CH_{1.44}O_{0.66}$ describes the average composition of typical biomass used for combustion, i.e., wood, straw, or similar. As a result of the combustion process, different types of pollutants can be distinguished:

1. Uncombusted pollutants such as CO, C_XH_Y, PAH, tar, soot, carbon, H_2, HCN, NH_3, and N_2O

2. Pollutants from complete combustion such as NO_X (NO and NO_2), CO_2, and H_2O

3. Ash and contaminants such as ash particles (KCl, etc.), SO_2, HCl, PCDD/F, Cu, Pb, Zn, Cd etc.

3.5 Reduction of airborne pollutants

3.5.1 Staged combustion

If *staged combustion* is applied, the excess air can vary in different sections. *Two-stage combustion* is applied with primary air injection in the fuel bed and consecutive secondary air injection in the combustion chamber. This allows good mixing of combustion air with the combustible gases formed by devolatilization and gasification in the fuel bed. If good mixing occurs, an operation at low excess air is possible (i.e., excess air lambda < 1.5), thus enabling high efficiency and high temperature (Figure 3.4) with complete burnout (Figure 3.5). If good mixing is achieved, the concentrations of uncombusted pollutants can be reduced to levels close to zero (e.g. CO < 50 mg/m^3 and C_XH_Y < 5 mg/m^3 at 11 vol.-% O_2). However, an accurate process control (e.g. CO/lambda-controller with use of sensors for CO and lambda) is needed to ensure optimum excess air in practice. For this purpose, self-adjusting control systems with use of sensors for CO and lambda (CO/lambda-controller) or for CO and temperature have been developed.

Air staging applies air injection at two levels. In addition to conventional two-stage combustion, primary air needs to be understoichiometric (lambda primary < 1). A relevant residence time (and a reduction zone in the furnace leading to an enlarged furnace volume) is needed between the fuel bed and the secondary air inlet.

In *fuel staging*, fuel is fed into the furnace at two different levels. The primary fuel is combusted with excess air > 1. A consecutive reduction zone is achieved by feeding secondary fuel and late inlet of final combustion air for the secondary fuel. Both air staging and fuel staging have been developed as primary measures for reduction of fuel NO_X in biomass combustion and are described below.

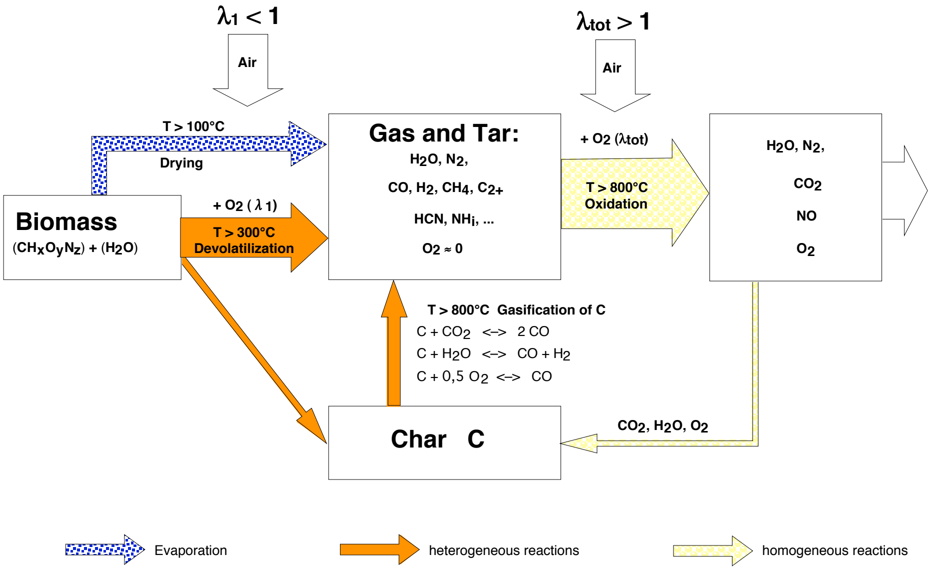

Figure 3.3 Reactions during biomass combustion by injection of primary air for gasification and secondary air for gas-phase burnout

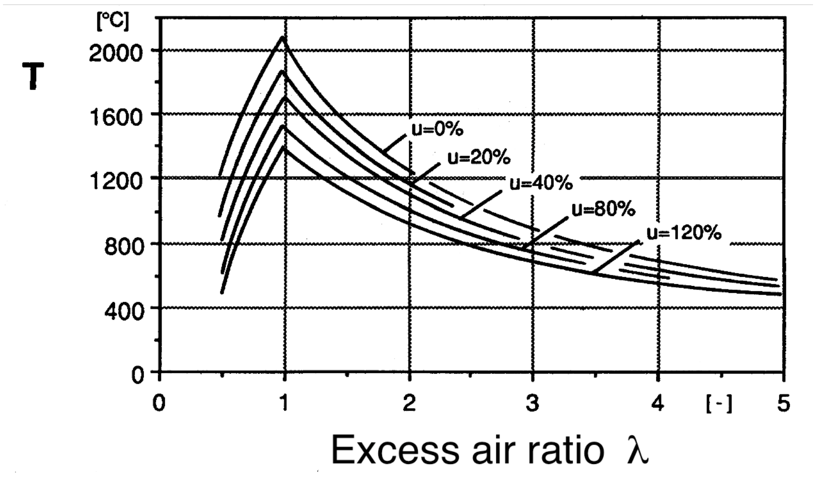

Figure 3.4 Adiabatic flame temperature for the combustion of wood with different humidity u (u is based on dry fuel, hence u = 100% corresponds to a moisture content w = 50%)

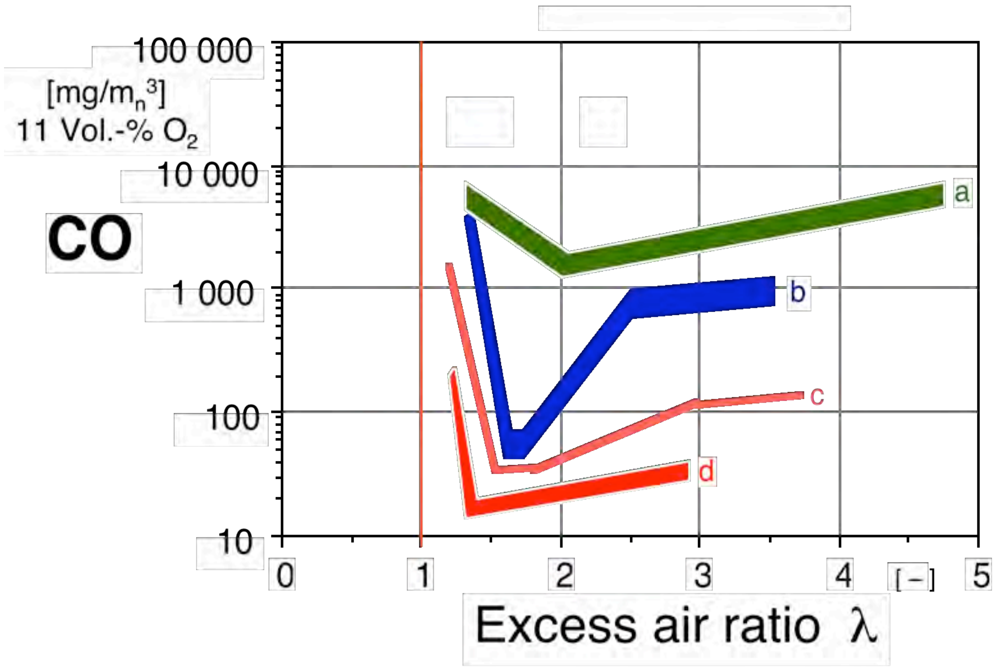

Figure 3.5 Carbon monoxide emissions as function of excess air ratio for different furnace types. a) Wood stove, b) downdraft boiler, c) automatic wood boiler, d) advanced automatic wood boiler

3.5.2 Uncombusted pollutants

The main needs for complete burnout are temperature, time, and turbulence (TTT). The mixing between combustible gases and air is identified as the factor that is most limiting to the burnout quality, while the demands for temperature (around 850°C) and residence time (around 0.5 s) can easily be achieved. Sufficient mixing quality can be achieved in fixed-bed combustion by the above-described two-stage combustion. In a fluidized bed, good mixing is achieved in the bed and the free-board and dust combustion easily allows good mixing.

For future improvements in furnace design, computational fluid dynamics (CFD) can be applied to calculate flow distributions in boilers. Furthermore, the reaction chemistry in the gas phase is also well known and can be implemented in CFD codes. However, the heterogeneous reactions during drying, transport, devolatilization, and gasification of solid biomass before entering the gas phase combustion need to be considered and needs further improvement to allow the application of whole furnace modeling.

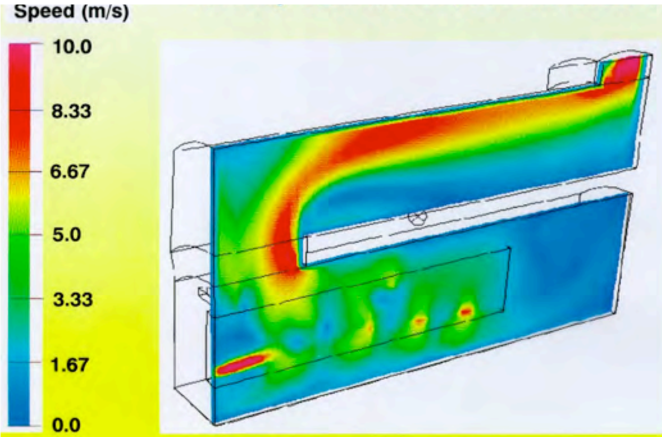

Figure 3.6 CFD modelling for optimization of furnace design - the example shows the velocity distribution in the combustion chamber over a grate with secondary air nozzles and post combustion chamber [Nussbaumer 2003].

3.5.3 NO_x emissions

In combustion processes, NO and NO_2 (summarized as NO_x) can be formed in three different reactions. Thermal NO_x and prompt NO_x are formed from nitrogen in the air at high temperatures and in the case of prompt NO_x in the presence of hydrocarbons. Fuel NO_x can be formed from nitrogen containing fuels. For biomass combustion, fuel-bound nitrogen is the main source of NO_x emissions, while thermal and prompt NO_x are not relevant due to relatively low temperatures, as has been shown by theoretical and experimental investigations.

Fuel nitrogen is converted to intermediate components such as HCN and NH_i with i=0, 1, 2, 3. These can be oxidized to NO_x if oxygen is available, which is the case in conventional combustion. If no oxygen is present, intermediates can interact in the reduction zone and form N_2 in reactions such as $NO + NH_2 = N_2 + H_2O$ (Figure 3.7). During the past 10 years, staged combustion technologies have been developed as a primary measure for internal NO_x reduction based on this concept, thus leading to the above-described techniques of air staging and fuel staging (Figure 3.8). Both measures allow a NO_x reduction of up to 50% for wood with low nitrogen content and up to 80% for bio fuels with high nitrogen content. However, different specific conditions have to be met accurately to exhaust this reduction potential.

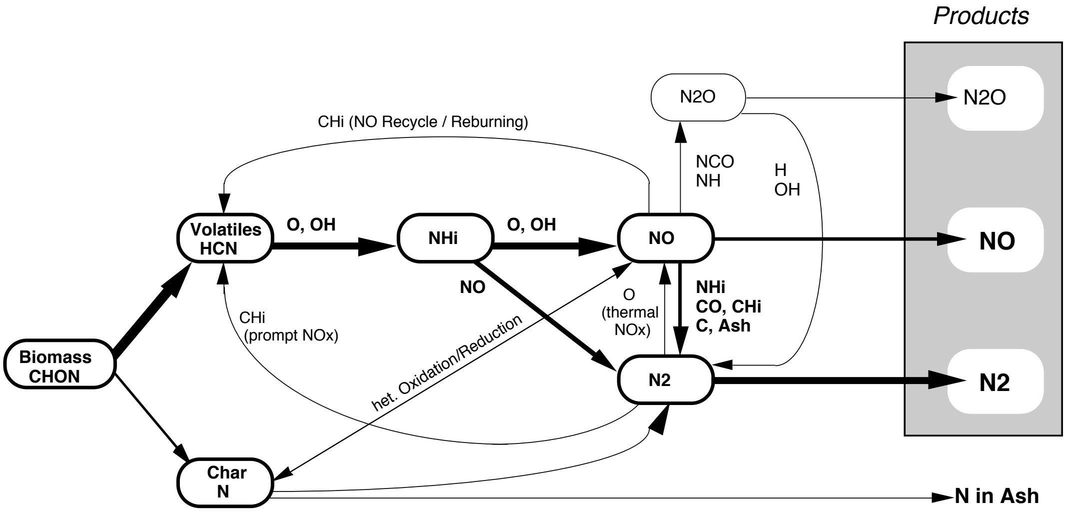

Figure 3.7 Conversion of fuel nitrogen in biomass combustion [Nussbaumer 2003]

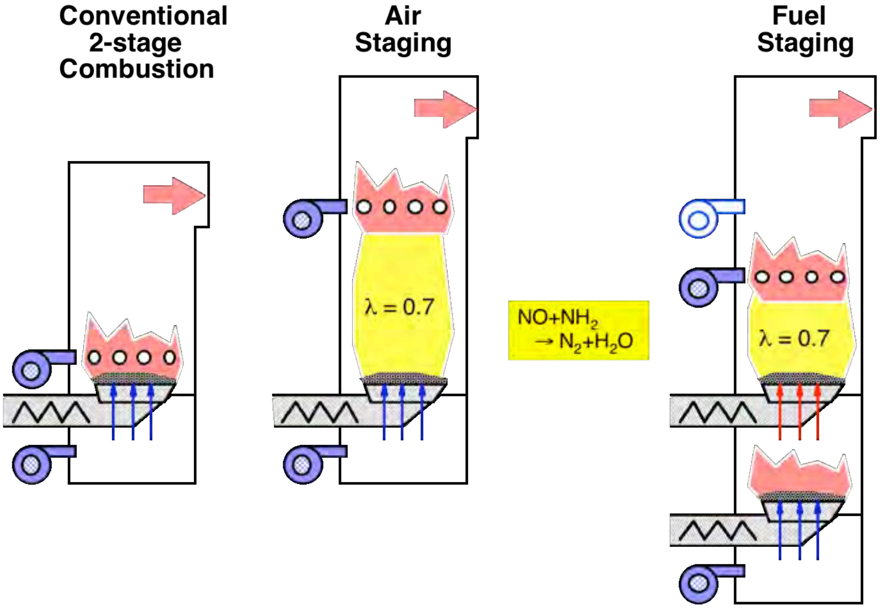

Figure 3.8 Principle of conventional two-stage combustion, air staging with reduction zone, and fuel staging with reduction zone [Nussbaumer 2003]

In the case of air staging, a primary air excess around 0.7, a temperature in the reduction zone of 1150°C, and a residence time of 0.5 s are needed. The relatively high temperature can limit the application in practice due to undesired ash softening and deposit formation. For fuel staging, similar results are achieved at lower temperatures (i.e., at temperatures as low as 850°C). However, the furnace concept and operation is more complex due to the need of two independent fuel feeding systems. Nevertheless, a pilot plant based on this concept has been successfully designed with a combination of understoker furnace and entrained flow reactor. For both types of staged combustion, accurate process control is needed to ensure an operation at the excess air ratio needed in the different zones.

Beside primary measures, secondary measures are available for NO_x abatement. The most relevant techniques are selective noncatalytic reduction (SNCR) and selective catalytic reduction (SCR) using the same reaction as mentioned for staged combustion, i.e., $NO + NH_2 = N_2 + H_2O$. However, urea or ammonia is injected as a reducing agent and as a source of NH_2. SNCR has to be applied in a narrow temperature window of around 820°C to 940°C, thus allowing a NO_x reduction up to 90%. SCR is typically applied in the flue gas in a temperature range of 250° to 450°C and allows a NO_x reduction of more than 95%. However, relevant concentrations of undesired side products such as HNCO, N_2O, NH_3, HCN, and others can be formed in both types of secondary measures under unfavorable conditions. Primary measures are preferable if they can achieve sufficient emission reduction.

3.5.4 Particulate emissions

Biomass combustion leads to relatively high emissions of particulates. The majority of the particulates are smaller than 10 micron (μm) (i.e., particulate matter PM_{10}) with a high share of submicron particles (PM_1).

Submicron and supermicron particles in fluidized-bed combustion are composed of fine particles of K, Cl, S, Na and Ca and coarse particles of Ca, Si, K, S, Na, Al, P, Fe. In fixed-bed combustion, increasing mass concentrations of particulate emissions are typically related to increasing mean diameter. A dependency of the particle composition on size can also be found in fixed bed conditions, as K, S, Cl and Zn is mainly found in the submicron fraction, while the content of Ca is increasing with increasing particle size. If almost complete burnout is achieved by appropriate furnace design, the resulting particulates are almost exclusively formed from ash components in the fuel with salts such as KCl as main components. The main fuel constituents, with respect to aerosol formation, are typically K, Cl, S, Ca, Na, Si, P, Fe, and Al. Primary measures that can safely meet a high reduction potential by at least a factor of 10 in this category of aerosols are not known so far.

Recently a new approach for primary particle reduction has been presented. It was shown that particles from wood combustion are mainly formed by nucleation, coagulation, and condensation in the boiler during a decreasing temperature. Further, these particles are mainly salts and consist mainly of K. K is present as a salt in the fuel with a high melting point and devolatilization temperature. If oxygen is available at a high temperature, a high share of K can be oxidized. K oxides have significantly lower devolatilization temperatures than the K salts, and they are almost completely vaporized into the gas phase and lead to particle formation from the gas phase. If no oxygen is present in the fuel bed, the conversion of K to volatiles may be reduced, since the majority of K salts can be converted into the grate ash. Since a similar behavior for other ash components in the fuel is assumed, the oxygen content during the solid fuel conversion is regarded as a key parameter for aerosol formation.

According to this hypothesis, an experimental setup was designed based on an understoker furnace that allows a wood combustion with extremely low primary air in the fuel bed (or glow bed) on the grate. At such operational conditions, the glow bed height increases significantly, and the furnace design must be adapted. Furthermore, combustion becomes unstable below a certain primary air excess, and an accurate process control is needed. Results from a laboratory furnace show that a reduction of inorganic particle emissions by a factor of 5 is achievable. The results are in accordance with the theory, although other effects may influence the particle formation.

Nevertheless, since fuel composition is the main parameter for aerosol formation, secondary measures are necessary for further reduction in the future. Among those measures, fabric filters are promising due to their high separation efficiency, while electrostatic precipitation is more robust for practical applications.

3.6 Combustion technologies

Biomass combustion is mainly used for heat production in small and medium scale units such as wood stoves, log wood boilers, pellet burners, automatic wood chip furnaces and straw-fired furnaces. District heating systems range in size from 0.5 MW_{th} to 5 MW_{th} with some applications up to 50 MW_{th}. Combined heat and power production (CHP) with biomass is applied by steam cycles (Rankine cycle) with steam turbines, steam engines, and organic Rankine cycles (ORC) that have typical power outputs between 0.5 MW_e and 10 MW_e. Stirling engines (10 kW_e to 100 kW_e) and closed gas turbines are in development or demonstration mode. Co-firing in fossil fired power stations allows the advantages of large size plants (> 100 MW_e), which are not applicable for dedicated biomass combustion due to limited local biomass availability.

Table 3.2 gives an overview of the most frequently used furnace types for biomass combustion. The various types can be distinguished by the flow conditions in the furnace. There are three different flow conditions: fixed-bed, fluidized-bed, and entrained flow or dust combustion (Figure 3.9). To achieve complete burnout and high efficiencies in small-scale combustion, downdraft boilers with inverse flow have been introduced, which apply the two-stage combustion principle described above (Figure 3.10). An operation of log wood furnaces at very low load should be avoided, as it can lead to high emissions of uncombusted pollutants. It is recommended to couple log wood boilers to heat storage tanks.

Since wood pellets are well suited for automatic heating at small heat outputs as needed for today's buildings, pellet furnaces are an adequate application with growing propagation. Thanks to the well-defined fuel at low water content, pellet furnaces can easily achieve high-combustion quality. They are applied both as stoves and as boilers.

Understoker furnaces are mostly used for wood chips and similar fuel with relatively low ash content (Figure 3.11), while grate furnaces can also be used for high ash and water content (Figure 3.13).

Figure 3.12 shows the principle of a the "low particle concept", which was introduced by Verenum and Mueller AG and consists of a primary zone acting as a gasification section at very low primary excess [Oser & Nussbaumer 2006]. This principle allows the reduction of particle emissions by 50% to 80%. The following mechanisms are relevant for particle reduction:

- Reduced temperature in the glow bed reduces evaporation of ash constituents and formation of salts such as KCl in the flue gas.
- Reduction of gas velocity through the fuel bed reduces entrainment of fuel particles that enter the hot section in the flame, where released vapours from ash constituents remain in the flue gas. This leads to salts in the stack instead of grate ash.
- A reduction of the oxygen content in the fuel bed reduces the tendency to form oxides from the ash constituents, which reduces evaporation because oxides exhibit lower evaporation temperatures.
- Finally, the high fuel bed may act as a filter for initially released particles.

The low particle concept is being investigated in research projects in Switzerland. It exhibits a potential for improvement. However, particle separation is still needed to achieve very low particle emissions for large-scale application. For medium-scale combustion (100 kW to 500 kW), the low particle principle may achieve emission limits of smaller than 50 mg/m^3 without secondary measures. Furthermore, it allows a reduction of the filter ash if applied for large-scale combustion equipped with particle removal.

This allows a cost reduction for the particle separation and a reduction of filter ash, which needs to be desposed as hazardous waste.

Special types of furnaces have been developed for straw that has very low density and is usually stored in bales. Besides conventional grate furnaces operated with whole bales, cigar burners and other specific furnaces are in operation.

Similar technologies are applied to residential pellet boilers (Figure 3.14). However, due to the higher fuel density and the homogeneous fuel properties, smaller auxiliary equipment such as stokers and electric motors can be used. Pellet boilers are smaller in size and exhibit lower cost than wood chip boilers of the same nominal heat output.

Stationary or bubbling fluidized bed boilers (SFB) as well as circulating fluidized bed boilers (CFB) are applied for large-scale applications and often used for waste wood or mixtures of wood and industrial wastes from the pulp and paper industry (Figure 3.15, Figure 3.16). In CFB boilers, nearly homogeneous conditions of temperature and concentrations can be achieved, thus allowing high burnout quality at low excess air. The choice of different bed materials in CFB offers additional opportunities for catalytic effects. In addition, the option of heat removal from the bed allows control of the combustion temperature and allows an operation at low excess air without excessive ash sintering. Since similar conditions for nitrogen conversion with air and fuel staging are attained, relatively low NO_X emissions are achieved.

Table 3.2 Types of biomass furnaces with typical applications and fuels-*Biomass covers typically less than 10% of the total fuel input. a = ash content (wt.-%), d = typical fuel size (diameter)

Application	Type	Typical size range	Fuels	Ash	Moisture content
Manual	Wood stoves	2 kW – 10 kW	dry wood logs	< 2%	5% – 20%
	Log wood boilers	5 kW – 50 kW	log wood, sticky wood residues	< 2%	5% – 30%
Pellets	Pellet stoves and boilers	2 kW – 25 kW	wood pellets	< 2%	8% – 10%
Automatic	Unterstoker furnaces	20 kW – 2.5 MW	wood chips, wood residues	< 2%	5% – 50%
	Moving grate furnaces	150 kW – 15 MW	all wood fuels and most biomass	< 50%	5% – 60%
	Pre oven with grate	20 kW – 1.5 MW	dry wood (residues)	< 5%	5% – 35%
	Understoker with rotating grate	2 MW – 5 MW	wood chips, high water content	< 50%	40% – 65%
	Cigar burner	3 MW – 5 MW	straw bales	< 5%	20%
	Whole bale furnaces	3 MW – 5 MW	whole bales	< 5%	20%
	Straw furnaces	100 kW – 5 MW	straw bales with bale cutter	< 5%	20%
	Stationary fluidized bed	5 MW – 15 MW	various biomass, d < 10 mm	< 50%	5% – 60%
	Circulating fluidized bed	15 MW – 100 MW	various biomass, d < 10 mm	< 50%	5% – 60%
	Dust combustor, entrained flow	5 MW – 10 MW	various biomass, d < 5 mm	< 5%	< 20%
Co-firing*	Stationary fluidized bed	total 50 MW – 150 MW	various biomass, d < 10 mm	< 50%	5% – 60%
	Circulating fluidized bed	total 100 – 300 MW	various biomass, d < 10 mm	< 50%	5% – 60%
	Cigar burner	straw 5 MW – 20 MW	straw bales	< 5%	20%
	Dust combustor in coal boilers	total 100 MW – 1 GW	various biomass, d < 2 – 5 mm	< 5%	< 20%

Conversion factors:

1 MMBtu = 1,000,000 Btu = 1055 MJ = 293.06 kWh

1 MMBtu/h = 1,000,000 Btu/h = 293.06 kW

1 kW = 3,412 Btu/h

1 MW = 3,412,000 Btu/h = 3,412 MMBtu/h

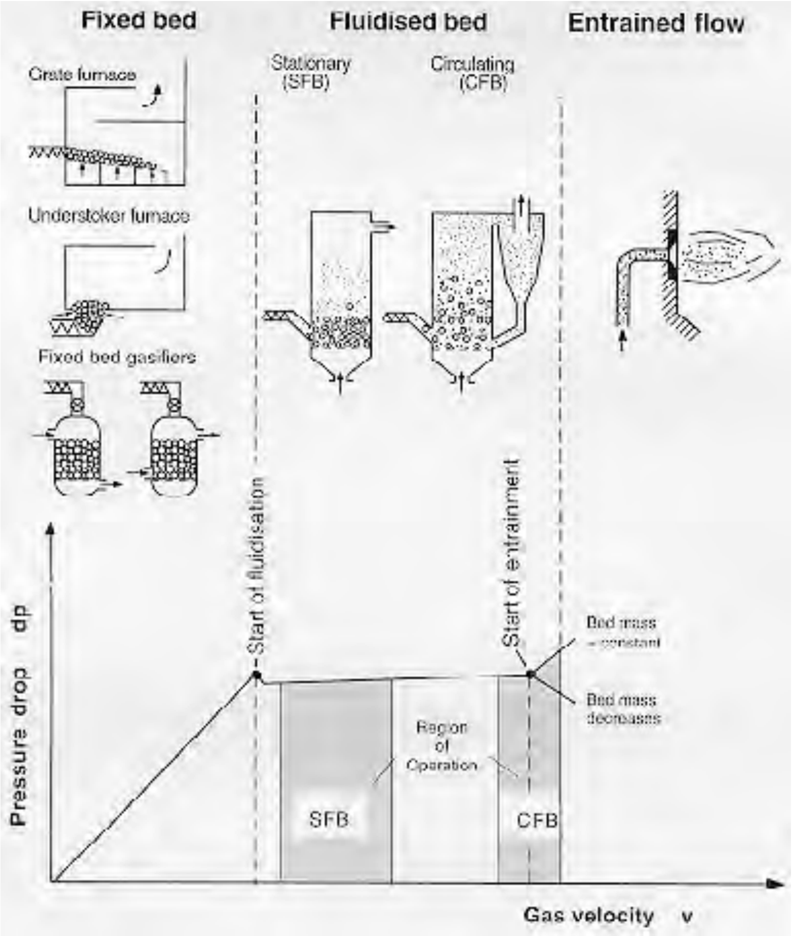

Figure 3.9 Furnace types and flow conditions: Fixed bed, fluidized bed, and entrained flow reactor

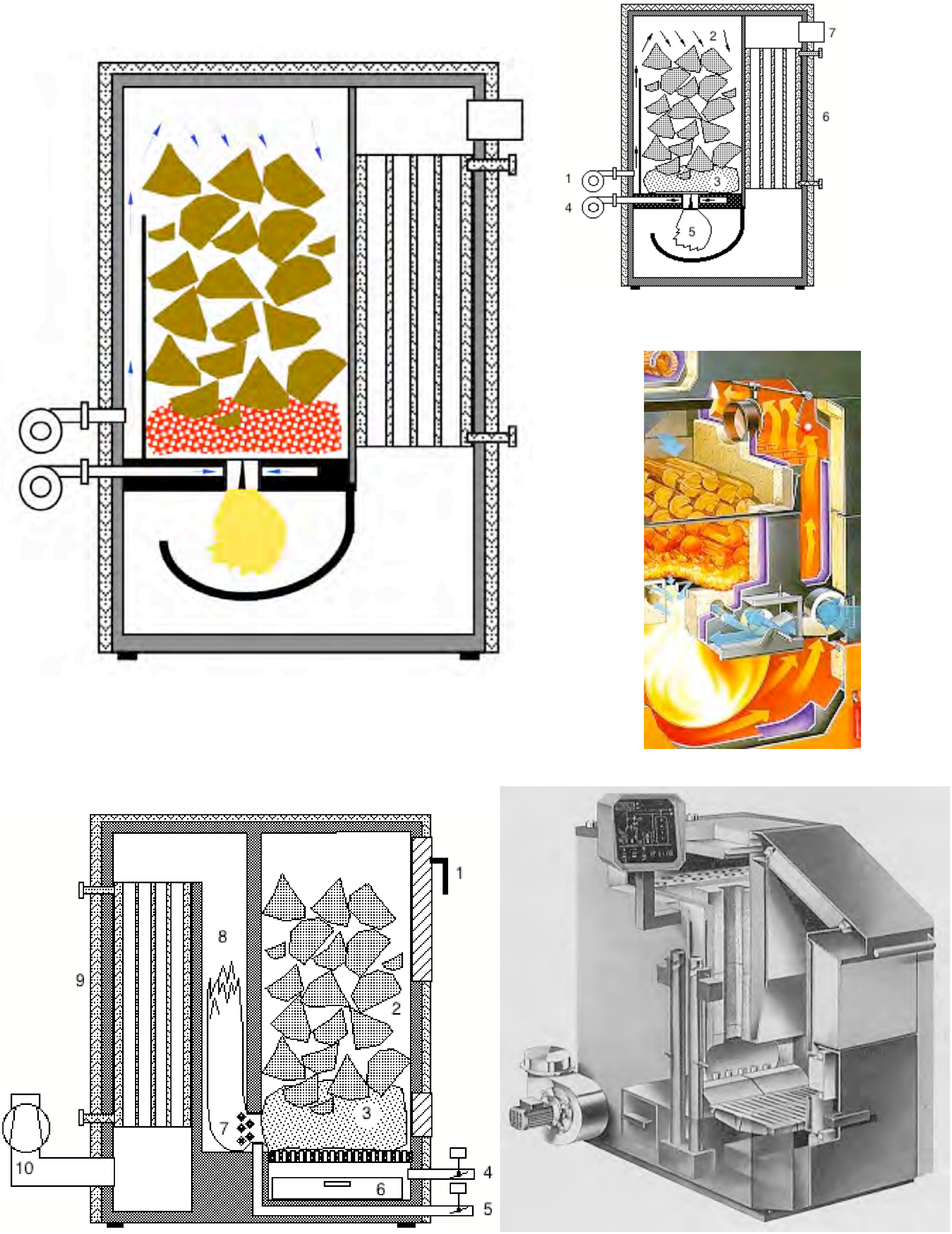

Figure 3.10 Downdraft boilers with inverse combustion of log wood and with enforced air flow and air supply with primary and secondary air. Top: 1 Primary air, 2 fuel hopper, 3 glow bed, 4 secondary air, 5 post combustion chamber, 6 heat exchanger, 7 chimney. Bottom: 1 Fuel inlet, 2 fuel hopper, 3 glow bed, 4 primary air, 5 secondary air, 6 ash bin, 7 mixing zone, 8 post combustion chamber, 9 heat exchanger, 10 chimney.

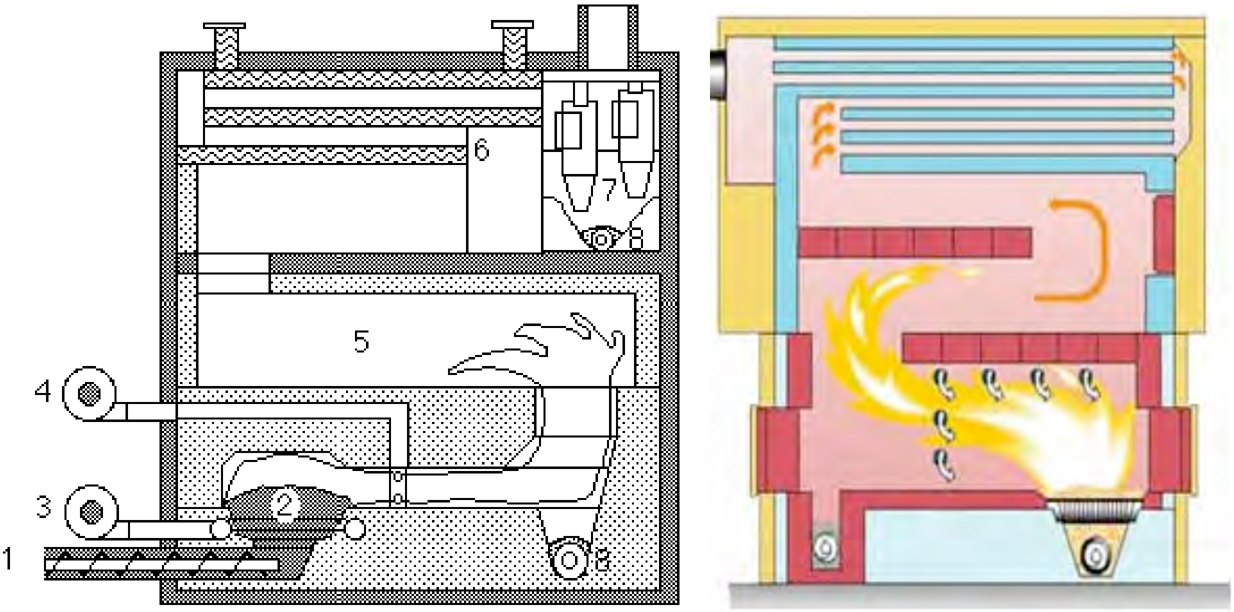

Figure 3.11 Understoker boiler with primary and secondary air, mixing zone and post combustion chamber. 1 Screw feeder, 2 understoker zone with glow bed, 3 primary air, 4 secondary air, 5 post combustion chamber, 6 heat exchanger, 7 cyclone, 8 ash removal.

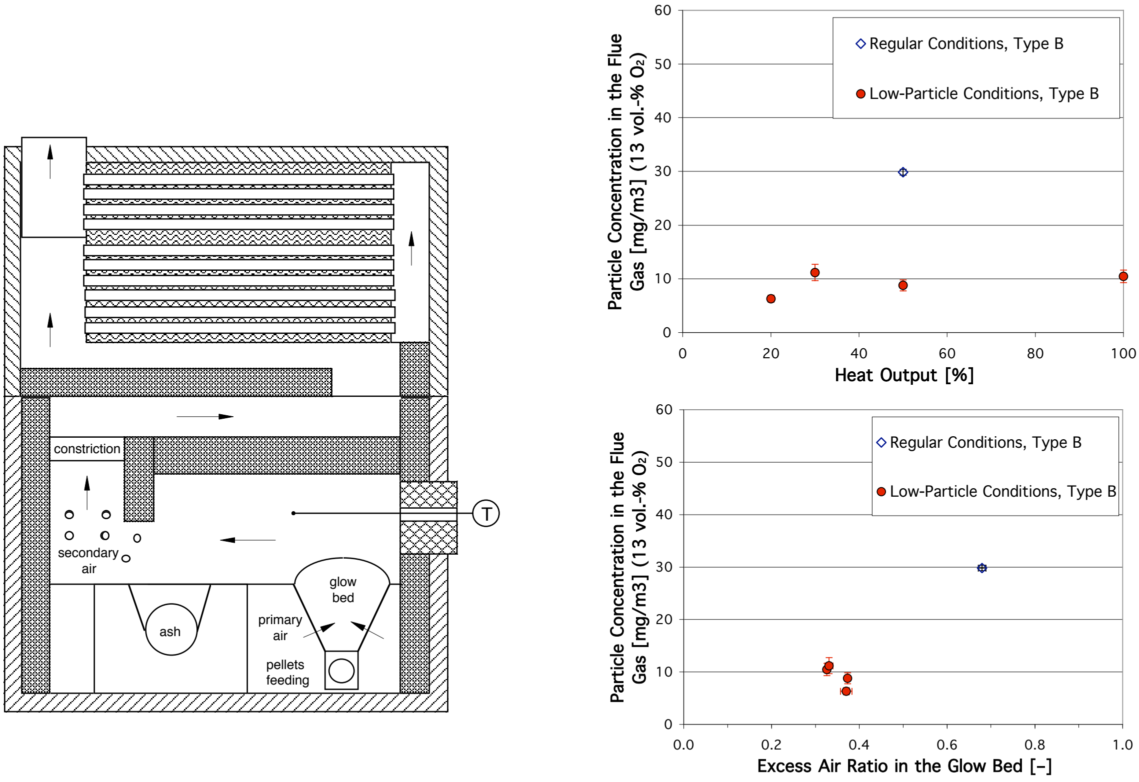

Figure 3.12 Schematic of an understoker boiler with "low particle concept" - The figure shows a 100 kW prototype pellet boiler. The cross-section of the combustion chamber is reduced from both sides in the section "constriction", to improve the gas mixing by acceleration and subsequent velocity reduction. The influence of low-particle conditions on the particle mass concentration is shown in the graphs. The reduction of the particle emissions at very low primary excess air (comparable to gasification conditions) amounts to more than 50%. The particle emissions remain constant at varying load, which is an important advantage for practical applications. [Oser & Nussbaumer 2006].

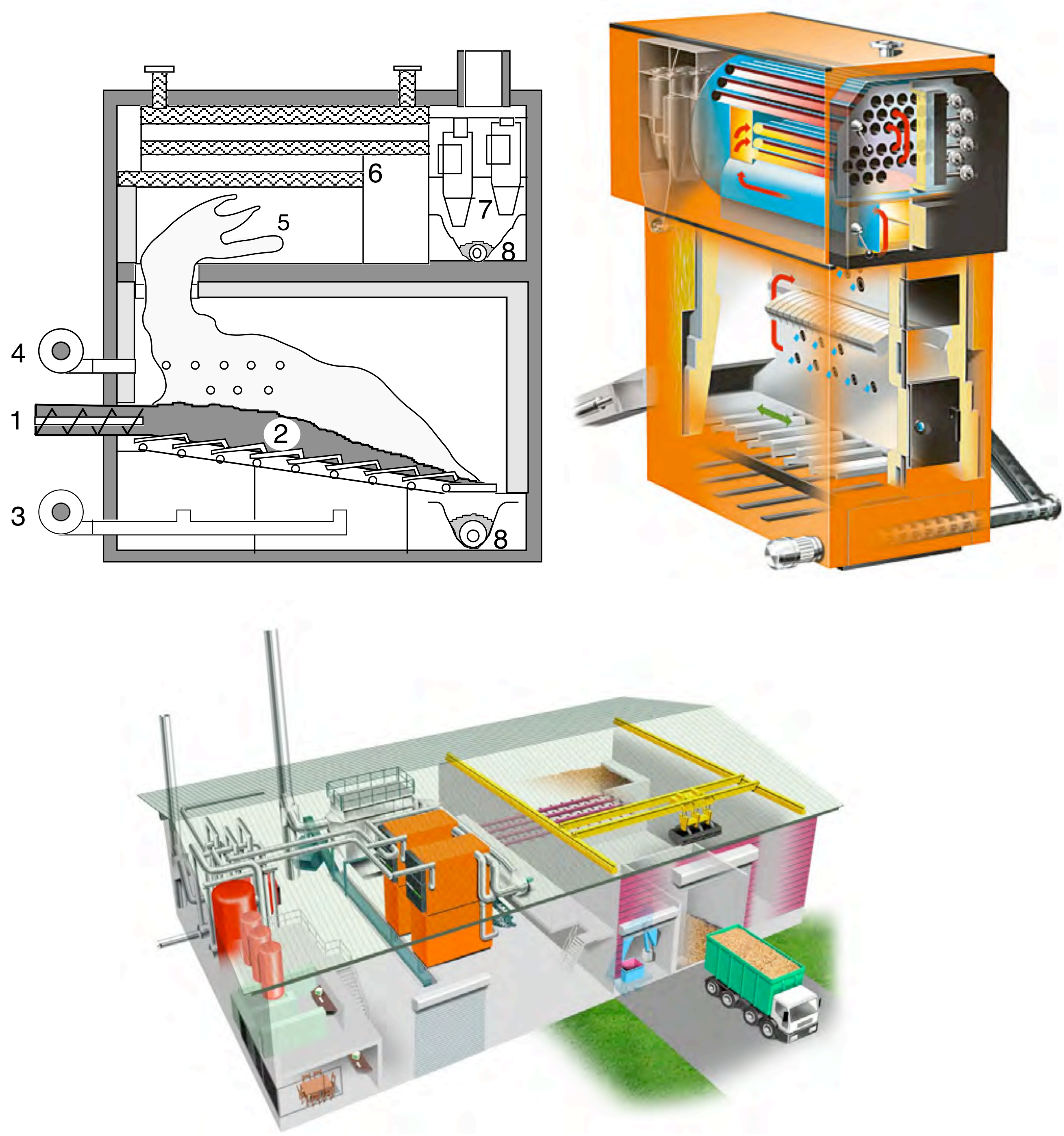

Figure 3.13 Moving grate boiler with primary air in two stages in the grate and secondary air.
Top: 1 Screw feeder, 2 moving grate, 3 primary air, 4 secondary air, 5 post-combustion chamber, 6 heat exchanger, 7 cyclone, 8 ash removal
Bottom: Example of a district heating plant with two boilers and electrostatic precipitator in Switzerland (app. 6 MW, Schmid)

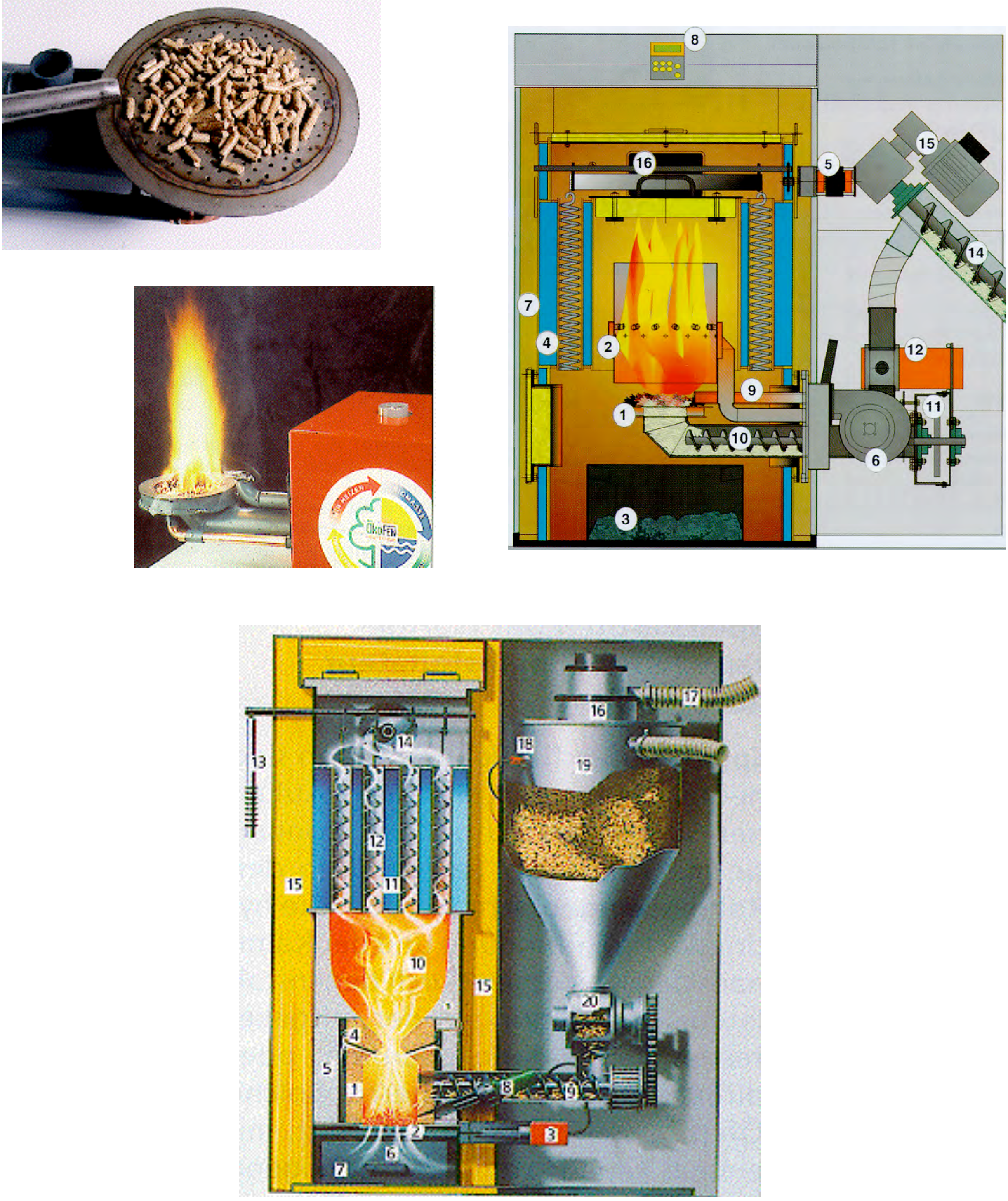

Figure 3.14 Examples of pellet boilers
Top: Understoker boiler with small grate and primary air inlet (1) and subsequent secondary air inlet in the combustion chamber (2) (Oekofen)
Bottom: Screw feeder on top of the grate with primary air inlet (6) and subsequent secondary air inlet (4) prior to the combustion chamber (10) (Hargassner)

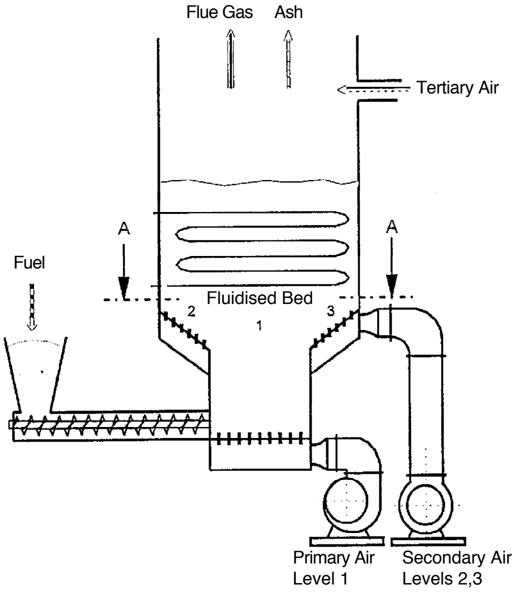

Figure 3.15 Stationary fluidized bed combustor with staged combustion. (Lurgi, 5 MW).

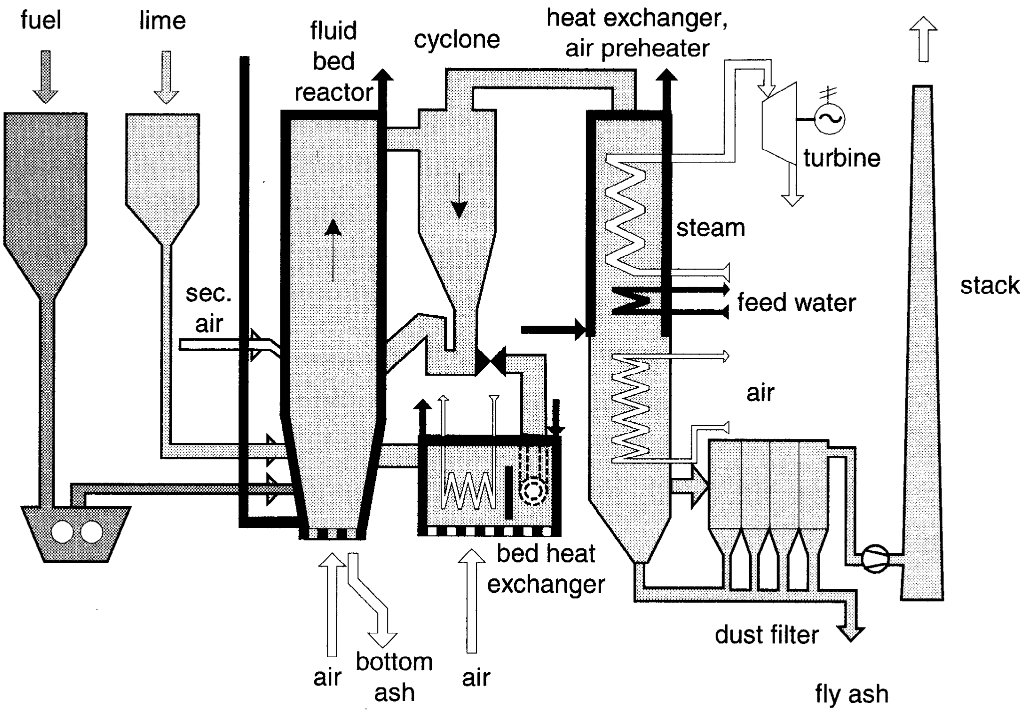

Figure 3.16 CFB plant with steam boiler for coal and biomass (Lurgi)

3.7 Co-combustion

A co-usage of biomass with other fuels can be advantageous with regard to cost, efficiency, and emissions. Lower specific cost and higher efficiencies of large plants can be used for biomass, and emissions of SO_X and NO_X can be reduced by co-firing. However, attention must be paid to increased deposit formation in the boiler and limitations in ash use due to constituents in biomass, especially alkali metals, which may disable the use of ash in building materials. Due to undesired changes of ash compositions, the share of biomass is usually limited to approximately 10% of the fuel input. Other opportunities are of interest, and the following three options for co-usage of biomass with coal are applied:

1. *Co-combustion or direct co-firing*: The biomass is directly fed to the boiler furnace (fluidized bed, grate or pulverized combustion), if needed after physical pre-processing of the biomass such as drying, grinding, or metal removal.
2. *Indirect co-firing*: The biomass is gasified and the product gas is fed to a boiler furnace (a combination of gasification and combustion).
3. *Parallel combustion*: The biomass is burned in a separate boiler for steam generation. The steam is used in a power plant with the main fuel.

Co-combustion of biomass leads to a substitution of fossil fuels and to a net reduction of CO_2 emissions. In many countries co-firing is the most economical technology to achieve the target of CO_2 reduction. Biomass co-firing can therefore be motivated by savings of CO_2 taxes.

4 Particulate Matter (PM)

4.1 Characteristics of particulate matter (PM)

Particulate matter describes the sum of airborne solid particles and droplets. Particle size is an important parameter for the characterization of particulate matter. According to different size ranges, coarse particles > 10 µm, fine particles (0.1–1 µm or 0.1–2.5 µm) and ultrafine particles < 0.1 µm are distinguished. PM_{10} defines particles as having an aerodynamic diameter < 10 µm. This includes both coarse and fine particles. The size and density affects the retention period and travel distances in the atmosphere. Coarse particles tend to settle to the ground within hours, while fine particles can remain in the atmosphere for several weeks. Furthermore, limit values for both particle emissions and ambient PM standards are indicated as mass concentrations. This does not account for the large surface area of fine particles, which can act as a potential carrier for toxic substances. Besides 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 that need to be considered. For typical conditions, approximately 90% of PM consists of fine and ultrafine particles [UBA 2005]. Since PM indicates only mass concentrations, there are considerations for further parameters such as particle number and toxicity, which might be considered 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 air. Coarse particles from primary aerosols originate mainly from mechanical processes (construction activities, road dust, re-suspension, and wind), 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 such as sulphur oxides (SO_2, SO_3), nitrogen oxides (NO, NO_2), ammonia (NH_3), and Non-Methane Volatile Organic Compounds (NMVOC). Reaction products are ammonium sulphates and ammonium nitrate. Aldehydes and ketones are oxidation products of NMVOC. The greatest producer of secondary aerosols are combustion processes (thermal power stations, industry, domestic heating: SO_2, SO_3 and NO_X), agriculture (NH_3), Diesel engines (NO_X and SO_2), use of solvents, chemical industry and petro chemistry (NMVOC) [UBA 2005]. Beside secondary aerosols that originate from NO_X and SO_X, secondary organic aerosols (SOA) can also contribute significantly to PM in the ambient air. Among other sources, incomplete combustion of wood is a potential source of SOA.

PM in the ambient air can be influenced by the following secondary reactions:

1. High molecular organic compounds (organic condensables, such as tar components) can be available in the vapour phase at flue gas temperature in the stack but can subsequently form additional particles or droplets by nucleation and condensation. This leads to an increase in particle number and mass or an increase in the particle mass concentration by adsorption on existing particles in the stack or in the ambient air.

2. Low molecular organic compounds (VOC) can form SOA by photochemical oxidation in the atmosphere and/or can increase the particle mass by adsorption on existing particles. Due to the added mass of oxygen, the total particle mass is additionally increasing.
3. PM in the ambient air can be reduced by evaporation of particles and droplets and by desorption of semi-volatile compounds adsorbed on the particles due to dilution in the ambient air, thus resulting in a reduced partial pressure of the respective compounds in the surrounding atmosphere.

Consequently, organic PM from residential wood heating in the ambient air can be underestimated if only solid particles detected on hot filters in the stack at 160°C (as by VDI norms) are taken into account. Investigations from diesel and wood combustion show a distinctive increase in PM concentration by dilution with ambient air at low dilution ratios. For wood stoves, an increase of 2.5 to 9 was found in a dilution tunnel (Figure 4.28) [Rhyde & Johansson 2007] where dilution ratios up to 10 are commonly applied. Investigations from diesel exhaust also show a significant initial increase of detected particles by dilution with ambient air with a dilution ratio of 20 (Figure 4.1) [Lipsky & Robinson 2006, Robinson 2007].

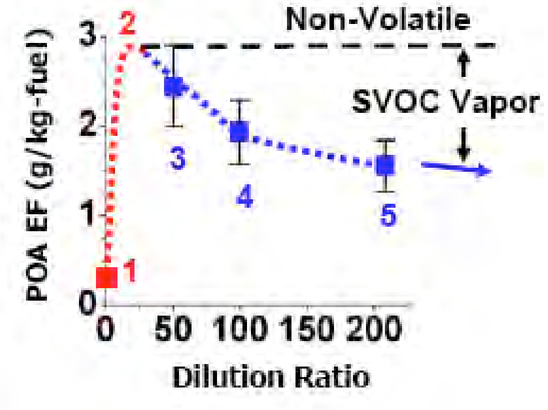

Figure 4.1 Primary organic aerosol (POA) in diesel exhaust as function of dilution ratio [Robinson 2007]
1: Measurement in undiluted exhaust (tail pipe)
2: Measurement with dilution with cold air at dilution ratio = 20
3, 4, 5: Measurement with further increased dilution

Cooling with subsequent condensation and adsorption is essential in the first dilution step and leads to a significant increase in particle mass. The further dilution of the flue gas, evaporation, and desorption of volatile and semi-volatile compounds due to a reduction of the partial pressure in the surrounding gas phase becomes relevant. This leads to a reduction of the particle mass. Consequently, the partitioning of semivolatile organics is a crucial factor with respect to the conversion of stack emissions from wood combustion or from diesel engines to the ambient air. Figure 4.2 illustrates the conversion mechanisms from emissions in the stack to ambient conditions by an initial rapid dilution and consecutive secondary reactions. This leads to additional secondary organic aerosols. The graph describes a fictitious example. However, the illustrated increase of detected solid particles in the hot flue gas to the particle mass sampled at a dilution ratio of approximately 10, corresponding to typical conditions in a dilution tunnel, is assumed to be 3.3 in the given example, which is in the range of results reported from wood stoves. The example describes a resulting PM_{10} concentration in the ambient, which is 2.8 times the mass of primary solid particles detected in the stack (i.e. in undiluted flue gas at a flue gas temperature of 160°C). The difference is due to secondary organic aerosols that result from organic compounds available as condensables at ambient conditions and additional particle mass resulting from secondary oxidation of volatile and semivolatile compounds. The sum of PM_{10} and VOC can exceed the mass of particles and condensables detected in the stack or immediately after an initial dilution, which is due to the added mass of oxygen available by secondary oxidation. To illustrate the potential effect of added oxygen, Figure 4.3 shows a fictitious example, where the resulting mass of PM_{10} exceeds the mass of solid particles and condensables in the stack.

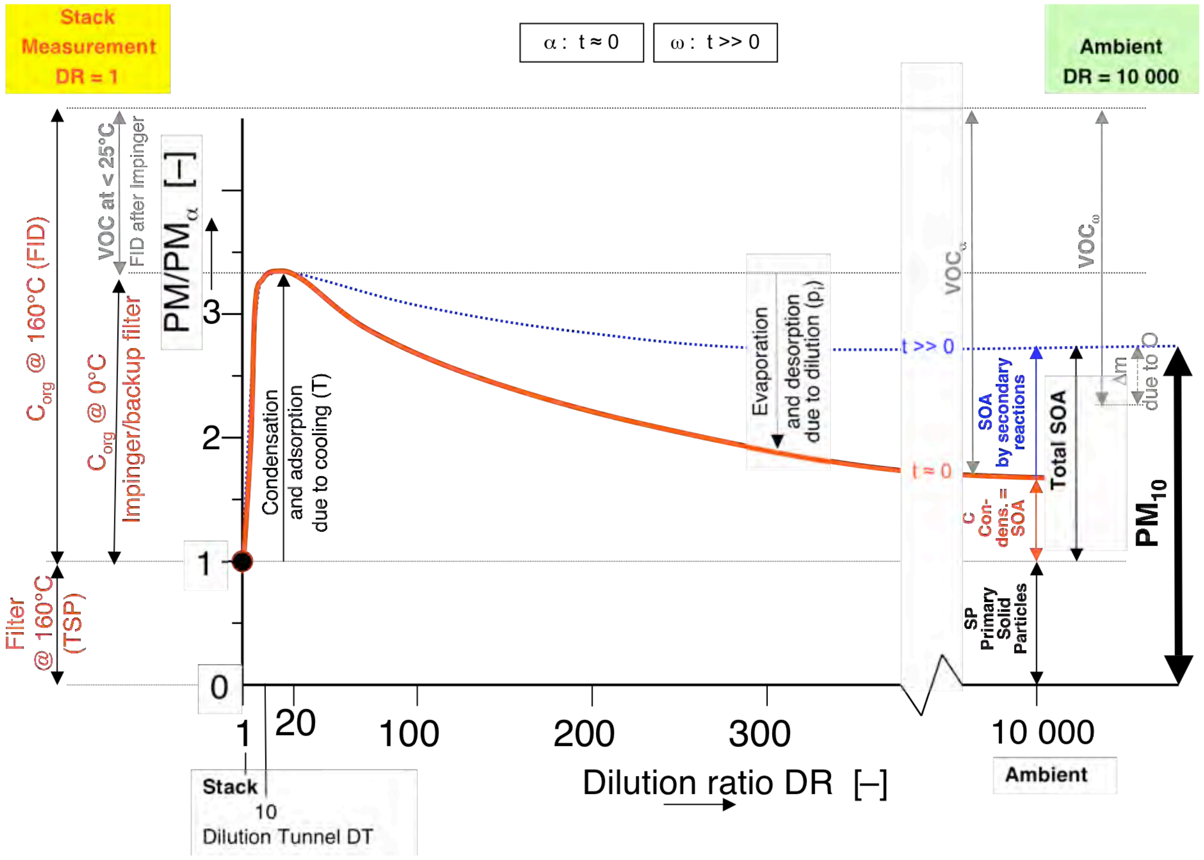

Figure 4.2 Conversion of stack emissions to PM_{10} in the ambient - The graph shows a virtual example with total SOA = 1.8 TSP as measured in the stack and consequently PM_{10} = 2.8 TSP

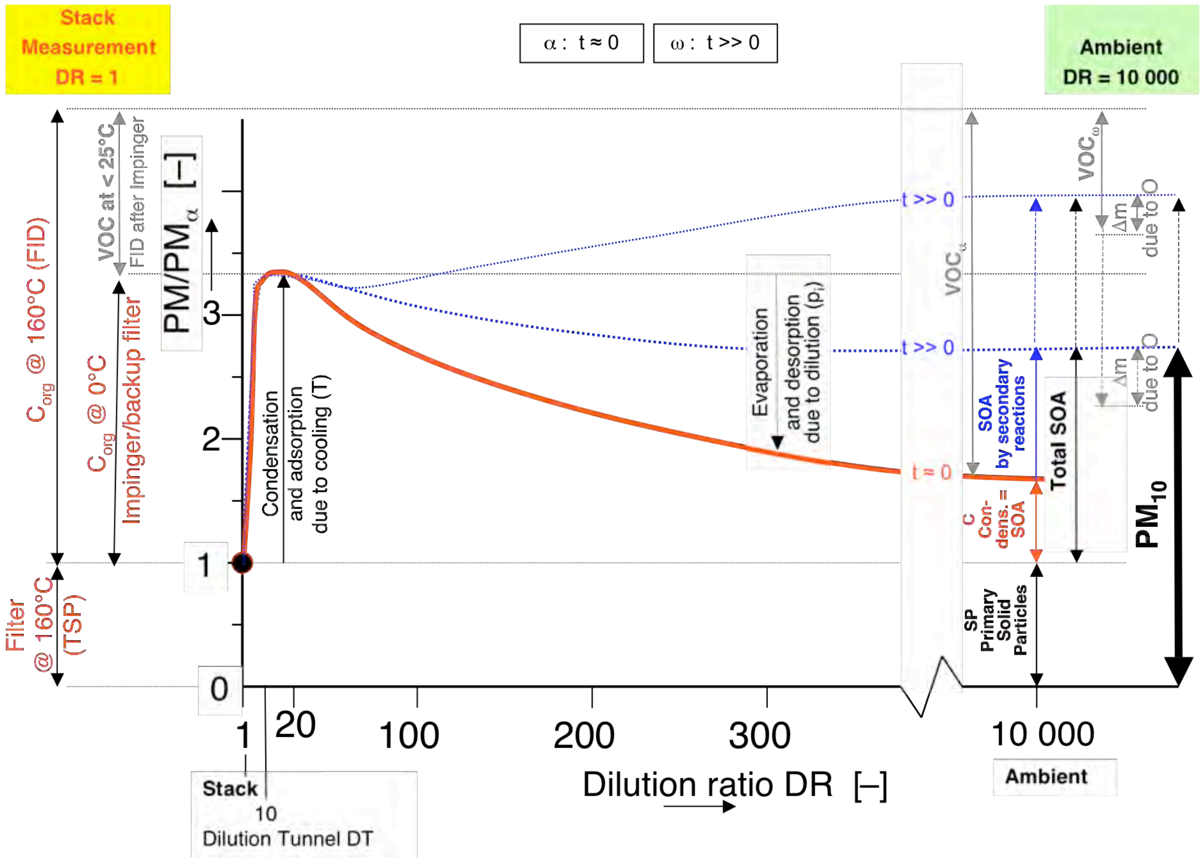

Figure 4.3 Conversion of stack emissions of PM and organics to PM_{10} in the ambient - The graph shows a virtual example with total SOA = 2.8 TSP as measured in the stack and consequently PM_{10} = 3.8 TSP. Here, the mass of PM_{10} in the ambient exceeds the total mass of solid particles and condensables as sampled in the stack due to the additional mass of oxygen added by secondary oxidation.

4.2 Health relevance of PM

Long exposures to particulate matter can cause serious health problems such as higher morbidity, effects on lungs, and a shorter life expectancy, mainly in subjects with pre-existing heart and lung diseases. Particle size is a main determinant of the effect on health. Coarse particles are generally filtered in the nose and throat while PM_{10} can settle in the lungs and may reach the alveolar region. Many regulatory agencies have agreed on 10 microns, as a measure between respirable and non-respirable particles, for monitoring ambient air quality. $PM_{2.5}$ and PM_1 are also used as indicators for air quality standards. The World Health Organization has published its Air Quality Guideline based on health effects with limit values for PM_{10} and $PM_{2.5,}$ for short-term and long-term exposures [WHO 2006]. The aim of the Air Quality Guideline (AQG) of the World Health Organization (WHO) is to support actions to achieve air quality that protect human health. Countries are encouraged by WHO to adopt an increasingly stringent set of standards, and track 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]. Besides the guideline value, three interim targets were defined, since countries may find these interim targets particularly helpful in gauging progress over time in the 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 4.1 and Table 4.2 summarize the current data on PM reported by WHO and proposed for annual and daily mean concentrations.

Table 4.1 WHO air quality guidelines and interim targets for particulate matter: annual mean concentrations. The use of PM2.5 guideline value is preferred.

	PM_{10} [µg/m^3]	**$PM_{2.5}$** [µg/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 theIT-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 4.2 WHO air quality guidelines and interim targets for particulate matter: 24 hour concentrations (99th percentile (days/year)

	PM_{10} [µg/m^3]	**$PM_{2.5}$** [µg/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

4.3 Ambient PM standards

Table 4.3 shows a comparison of ambient PM standards in different countries. The European Community has set limits for PM_{10} in the air in the directives 1999/30/EC and 96/62/EC. On Jan. 1, 2005 these standards became effective. In a first phase, the limit of the yearly average is 40 μg/m^3 and the daily average (24-hour mean) 50 μ g/m^3. The daily average is not allowed to be exceeded more than 35 times per year. In a second phase starting June 1, 2010, the yearly average standard will be 20 μg/m^3 and the daily average limit will be 50 μg/m^3. The daily average will be allowed to exceed this amount only 7 days per year.

Table 4.3 Ambient PM standards for PM_{10} (except USA: PM_{10} 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	35	98% for an average over 3 a

4.4 Types of combustion particles

Investigations on particle emissions showed that well-designed and properly-operated advanced-technology automatic wood combustion plants (mostly used in the size range > 200 kW) achieve a high combustion quality, which results in low emissions of uncombusted hydrocarbons and soot [Nussbaumer 2005]. However, automatic wood boilers exhibit fairly high mass concentrations of particle emissions in raw gas (typically a 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 or non-woody biomass). Particles from advanced-technology and well-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 advanced-technology automatic combustion devices are shown in Figure 4.4. From a poorly operated wood stove, soot particles, as well as tar droplets, can be identified as shown in Figure 4.5. In conditions with lack of oxygen in the combustion chamber, the particle mass concentration increases dramatically as shown in Figure 4.6. This is due to uncombusted soot and organic primary aerosols. As a result of agglomeration, the particle size distribution is shifted to larger particles. In addition, high concentrations of condensable organic matter and volatile organic compounds (VOC) are released with the flue gas, which are potential pre-cursors of secondary organic aerosols (SOA).

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. Significantly higher concentrations of polycyclic aromatic hydrocarbons (PAH) (Table 4.4) as well as far higher cell toxicity (Figure 4.7) and carcinogenic potential indicated by chromosome abberation (Figure 4.8) were found in particles and condensables from incomplete combustion of wood than in diesel soot [Klippel & Nussbaumer 2007 a]. Condensable organic substances such as tar components are a product of wood pyrolysis, which may occur under smoldering conditions such as a wood stove operated with reduced air inlet at low-burning rate and low temperature. Highly toxic PAH may also be formed as secondary tar in subsequent gas phase reactions in the combustion chamber under conditions with lack of oxygen [Morf et al. 2002].

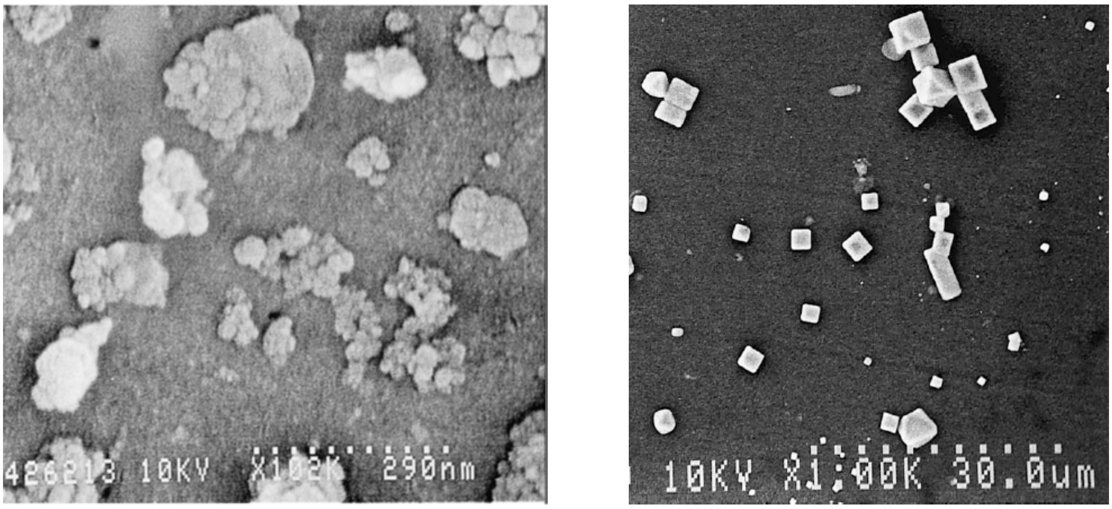

Figure 4.4 SEM-pictures of particles in the flue gas of an automatic wood combustion system. Left is the combustion of wood resulting in submicron particles. Right is the combustion of herbage grass resulting in larger particles at higher mass concentrations [Kaufmann et al. 2000].

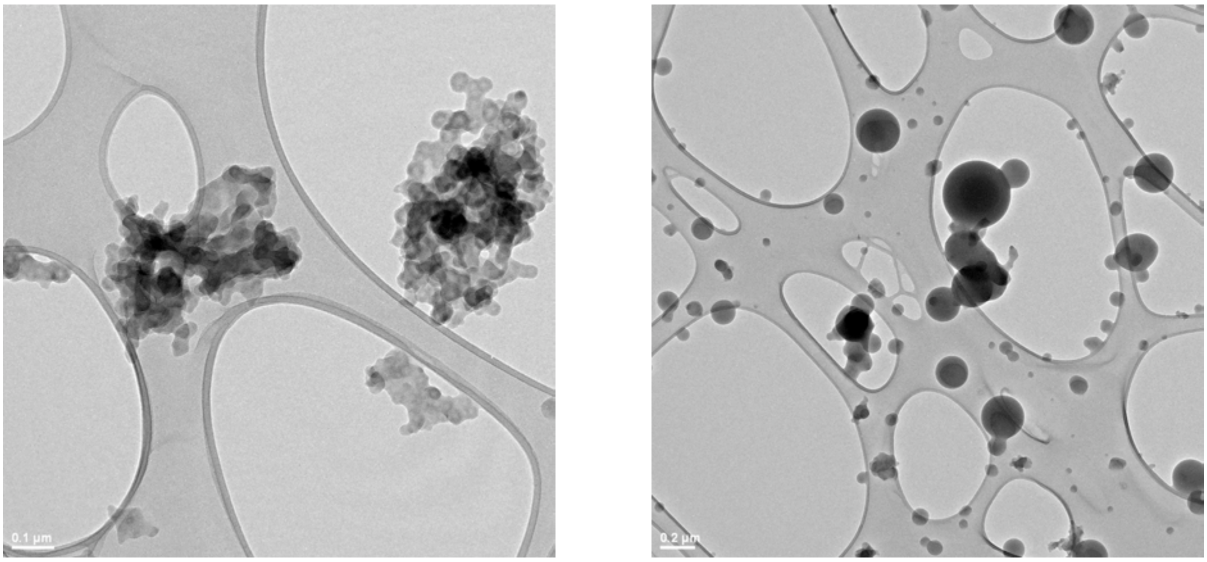

Figure 4.5 TEM-pictures of soot agglomerates (left) and tar droplets (right) from the flue gas of a poorly operated wood stove - Scale of white line in the left picture: 100 nm, right: 500 nm - Pictures from Heuberger, EMPA Dübendorf, published in [Klippel & Nussbaumer 2007 b].

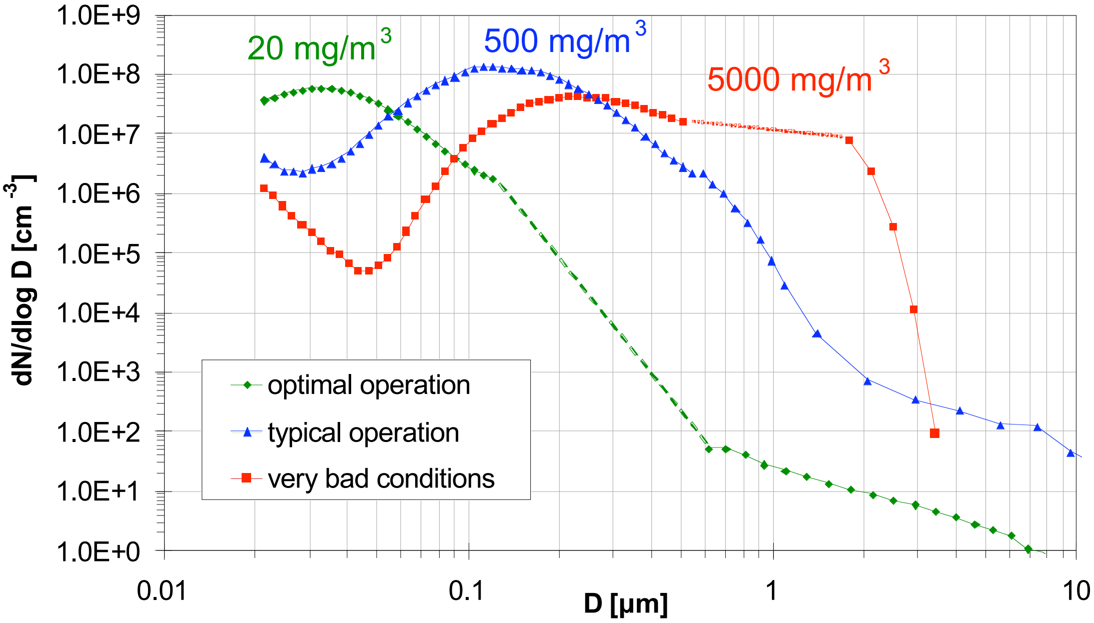

Figure 4.6 Number size distribution of particles from wood stoves under different operation conditions monitored in the size range from 20 nm to 10 µm by Scanning Mobility Particle Sizer (SMPS) and Optical Particle Counter (OPC) - Mass concentrations measured with gravimetric method according to VDI and indicating only solid particles without condensables at 13 Vol.-% O_2 [Klippel & Nussbaumer 2007 b]

Table 4.4 PAH concentrations in particles from badly operated wood stove and in Diesel soot [Klippel & Nussbaumer 2007 a].

mg/kg	Particles from wood stove	Diesel soot
Naphthalene	13	42
Acenaphthylene	129	7.1
Acenaphthene	17	< 3
Fluorene	173	< 3
Phenanthrene	231	3.7
Anthracene	65	< 3
Fluoranthene	154	< 3
Pyrene	170	< 3
Chrysene	54	< 3
Benzo(a)anthracen e	44	< 3
Benzo(b)fluoranthene	30	< 3
Benzo(k)fluoranthene	11	< 3
Benzo(a)pyrene	25	< 3
Indeno(1,2,3-cd)pyrene	9	< 3
Dibenzo(a,h)anthracene	< 8	< 3
Benzo(g,h,i)perylene	< 8	< 3
Total PAH	1 120	53

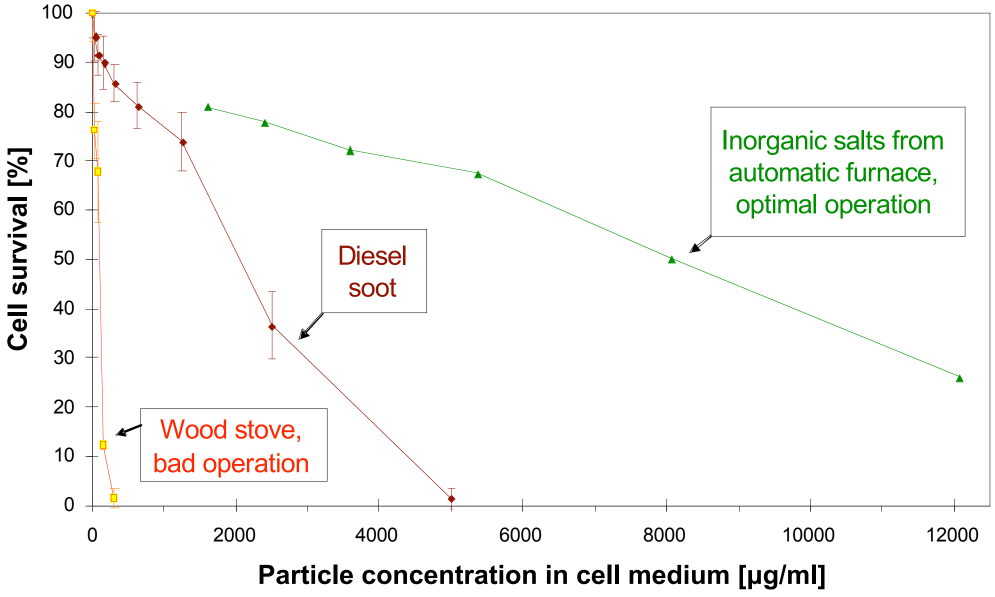

Figure 4.7 Cell survival as a function of particle concentration for Diesel soot, mainly inorganic particles from automatic wood combustion, and wood particles from incomplete combustion in a badly operated stove [Klippel & Nussbaumer 2007 b]

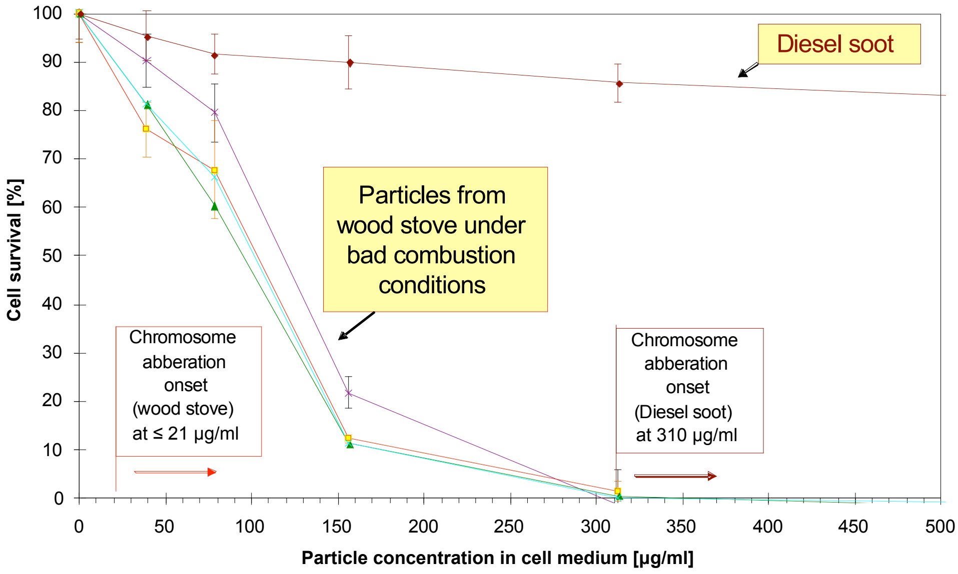

Figure 4.8 Cell survival as a function of particle concentration for Diesel soot and wood particles from incomplete wood combustion (data as in figure above but in magnified scale) - In addition, the level of chromosome aberration onset is indicated [Klippel & Nussbaumer 2007 b].

4.5 Influence of particle sampling methodology

Combustion particles are a mixture of solid particles and condensables, containing both organic and inorganic fractions. 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 such as benzo*(a)*pyrene (BaP) or fluorine. This 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.

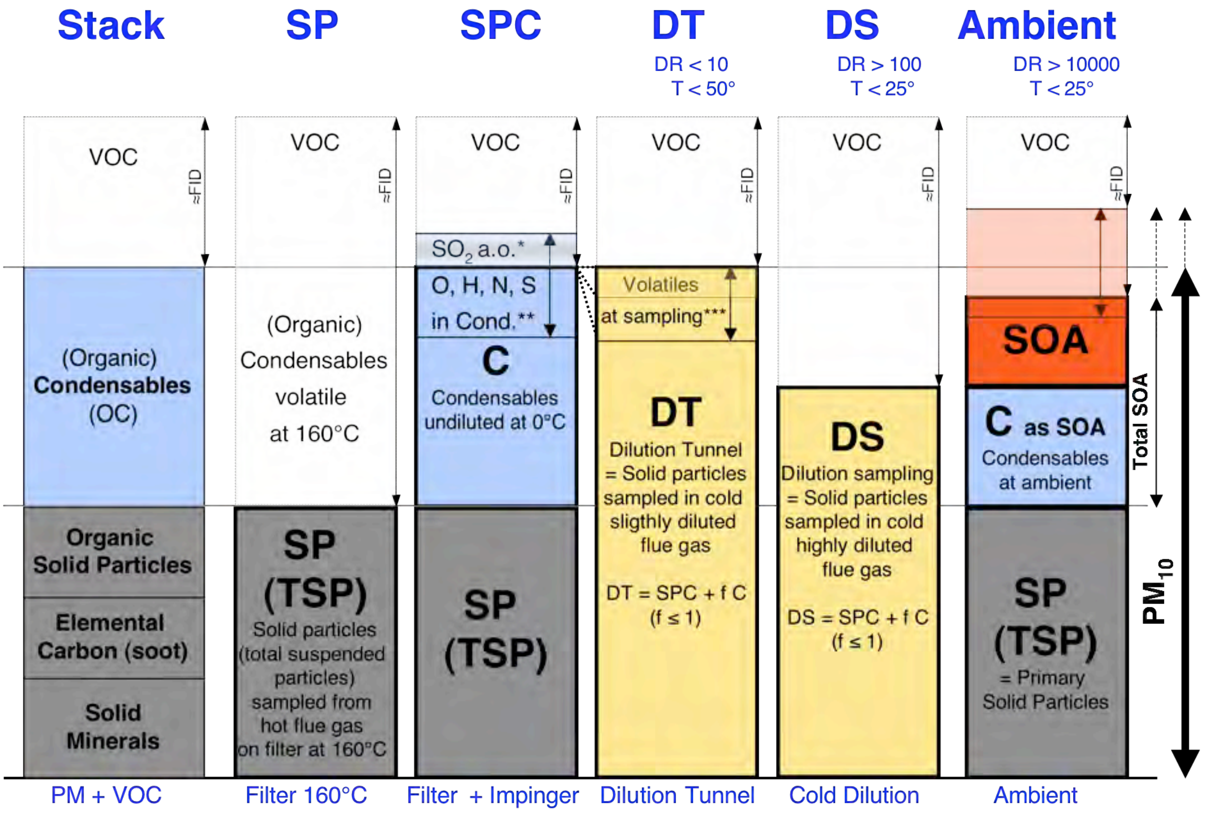

Figure 4.9 Comparison of PM sampling with PM in the ambient
SP: Filter (Method a) resulting in solid particles SP (total suspended particles TSP)
SPC: Filter + Impinger (Method b) resulting in solid particles and condensables SPC
DT: Dilution Tunnel (Method c) with typical dilution ratio (DR) in the order of 10 resulting in a PM measurement including SPC and most or all C. 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)
DS: Dilution Sampling with high dilution ratio (DR > 100)
PM$_{10}$: Total Particulate Matter < 10 microns in the ambient including SP and SOA
SOA: Secondary organic aerosols, consisting of condensables C at ambient and SOA formed by secondary reactions such as photochemical oxidation

*SO$_2$ and other soluable 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 that 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

The emission of inorganic particles can be slightly influenced by the combustion conditions. However, this depends on different formation mechanisms than organic particles. High temperature enhances the conversion of ash material to the gas phase and consequently, the emission of inorganic particles. Under typical conditions, organic particles are relevant in poorly operated manual wood combustion devices, while inorganic particles are dominant in automatic wood combustion plants operated at high temperatures. Depending on the aim of the measurement, different sampling strategies are commonly used for product testing and health studies. In the present survey, four types of particle sampling are distinguished, as illustrated in Figure 4.9:

A Sampling of particles on a heated filter, through a probe, from undiluted flue gas in the chimney at gas temperatures of 160°C (German norms by Verein Deutscher Ingenieure, VDI) or 120°C (US 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 otherwise indicated, 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 constituted a large part of K_2SO_4 and KCl (depending on the fuel composition) at favorable 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 method A, and subsequent sampling of **condensable organic matter (C)** in impinger traps at temperatures less than 20°C - Typically condensable particulate emissions are sampled in a series of impinger flasks 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 SO_2. In the case of a considerable 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 less than 35°C (Norwegian standard NS 3058-2). Due to the cooling, condensable organic material in the hot flue gas condenses on the filter. Condensable inorganic PM is assumed to be insignificant for residential combustion of wood. 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 and correspond to particles detected at small dilution ratios (DR) (typically DR has a magnitude of 10). For a comparison and interpretation of results from dilution tunnel measurements, it needs to be considered that the dilution ratio may vary during one measurement and from one measurement to another. This can lead to differences of the detected particle mass in regimes, where effects of condensation and re-evaporation are sensitive to the dilution ratio, as the initial dilution with cold air may lead to an increase of particle mass due to condensation. Further dilution may lead to a subsequent loss in particle mass due to re-evaporation of volatile compounds, as described in chapter 4.1.

D Dilution can also be performed at high dilution ratios (100 or more), which is defined as **dilution sampling (DS)** in the present study. To mimic conditions in the ambient air, sampling can be performed in cold, highly diluted flue gas. Dilution with cold air at high dilution ratios is applied by analyzing the plume by following a vehicle under real-world conditions in a certain distance on the road. As in dilution tunnels, the dilution ratio can vary during sampling.

For on-line analysis of the particle size and particle number concentrations, a hot dilution stage followed by a cold dilution stage is usually applied resulting in a total dilution ratio of 100. The hot dilution avoids condensation and allows to identify the particles similar as found in the stack (i.e. SP) but gathers information on the particle size and number instead of the particle mass.

For residential combustion devices, all methods can be applied, while for large combustion devices, sampling in a dilution tunnel is not applicable.

Sampling on hot filters by 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. Since condensable organic matter has been identified as highly toxic, method A may not only underestimate the mass concentration of PM, but the health impact as well.

Measurements in dilution tunnel by method C may over-estimate the particle mass in the ambient air, since evaporation by subsequent dilution in the ambient air may lead to a reduction in particle mass which, however, is then resulting in volatile organic matter instead of particulate matter as illustrated in Figure 4.2.

4.6 Measurement techniques

Table 4.5 shows a comparison of the most common methods for discontinuous measurements of particulate emissions, while Table 4.6 shows an overview of the covered size ranges and the advantages and disadvantages of continuous measurement methods.

Discontinuous gravimetric sampling of total particle mass concentration

The basic method used to measure mass concentrations of PM off-line in flue gases is gravimetric sampling of 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 pre-cyclone with a cut-off of 10 μm or 2.5 μm thus resulting in PM_{10} or $PM_{2.5}$. The sampling of particles on filters allows typical time resolution of 15 minutes and up and does not allow identification of fast dynamic processes. However, particles available on the filter are potentially available for additional chemical analysis.

Continuous measurements of particulate matter

When there is a need for real-time measurements of PM_{10} and $PM_{2.5}$, **Tapered Element Oscillating Micro-balance (TEOM)** is a well established instrument. TEOM is often used for measurement of PM_{10} and $PM_{2.5}$ in ambient air. In combustion applications, the ambient air model of the instrument is used with a dilution system. For larger combustion plants, there is a specific model of TEOM available that operates without dilution.

Continuous measurements of particle size distributions

Since the particle size is an important parameter that influences 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 the particle size 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 measurements with high-time resolution are of interest to detect transient conditions such as 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. They are sometimes combined with a filter that extends the measurement range 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

In terms of health concerns, 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 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)** is commonly used for measurement of concentration and corresponding size distribution. There are a number of instrument versions, working in the size range of a few nanometres to 1 μm.
- **Electric low-pressure impactor (ELPI)** is another instrument used for characterization of number concentration and distribution, which ranges from 7 nm to 10 μm.
- **Aerodynamic particle sizer (APS)** measures particles from ~0.5 μm to ~10 μm.
- **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 the number of particles, typically ranging from ~0.1 μm to a few micrometers.

The instruments mentioned use different particle diameters for characterization of number size distributions. It is important to respect which diameter is considered to perform conversions from number to mass concentration.

Particle properties

In addition to 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 be emphasized that characterization of chemical content is essential, as it can give information on combustion conditions and mirrors the ash content in the fuel.

Table 4.5 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 4.6 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

4.7 PM emission factors

4.7.1 Open fireplaces

Figure 4.10 shows the PM emission factors for open fireplaces as described in an overview on emission factors from different IEA countries [Nussbaumer et al. 2007]. The range for typical measured emission factors on solid particles (SP) varies between 23 and 265 mg/MJ (0.053 and 0.615 lb/MMBTU). National emission factors range from 160 (GER) to 447 mg/MJ (UKM) (0.371 and 1.04 lb/MMBTU). The emission factors for Finland and Norway are 860 mg/MJ and 910 mg/MJ (2.0 and 2.1 lb/MMBTU), respectively indicated for measurements with dilution tunnel (DT).

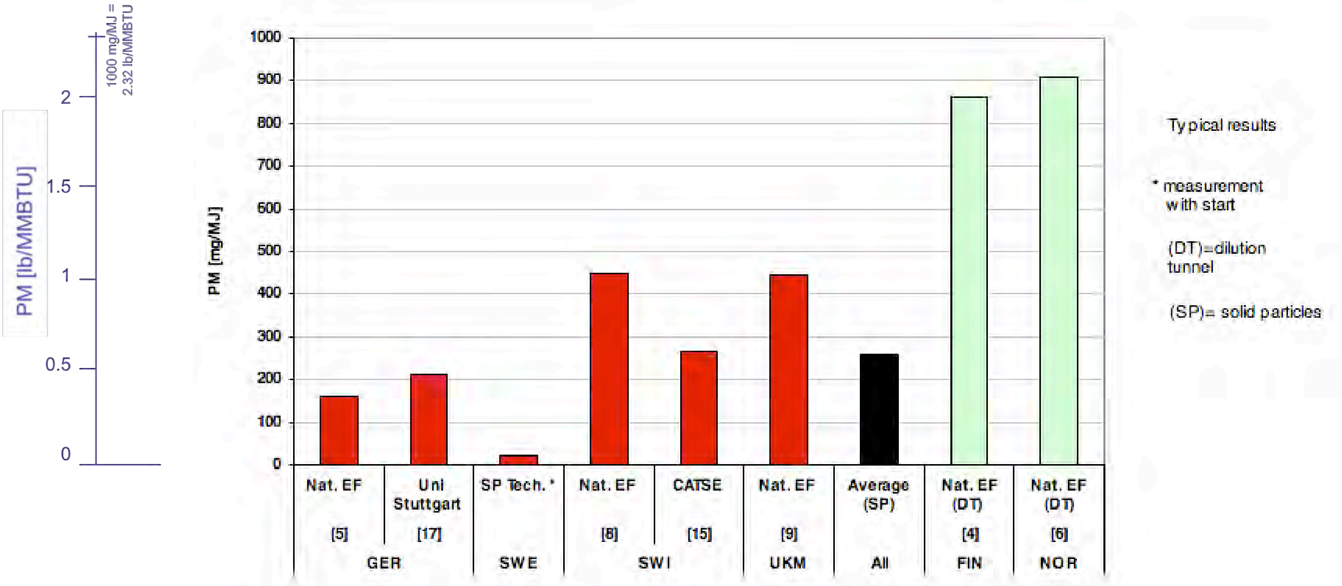

Figure 4.10 Emission factors for PM in mg/MJ for solid particles (red) and for particles measured in dilution tunnel (green)

4.7.2 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 (worst results from 0.42 – 0.47 lb/MMBTU, typical from 0.11 – 0.19 lb/MMBTU and best from 0.032 – 0.060 lb/MMBTU).

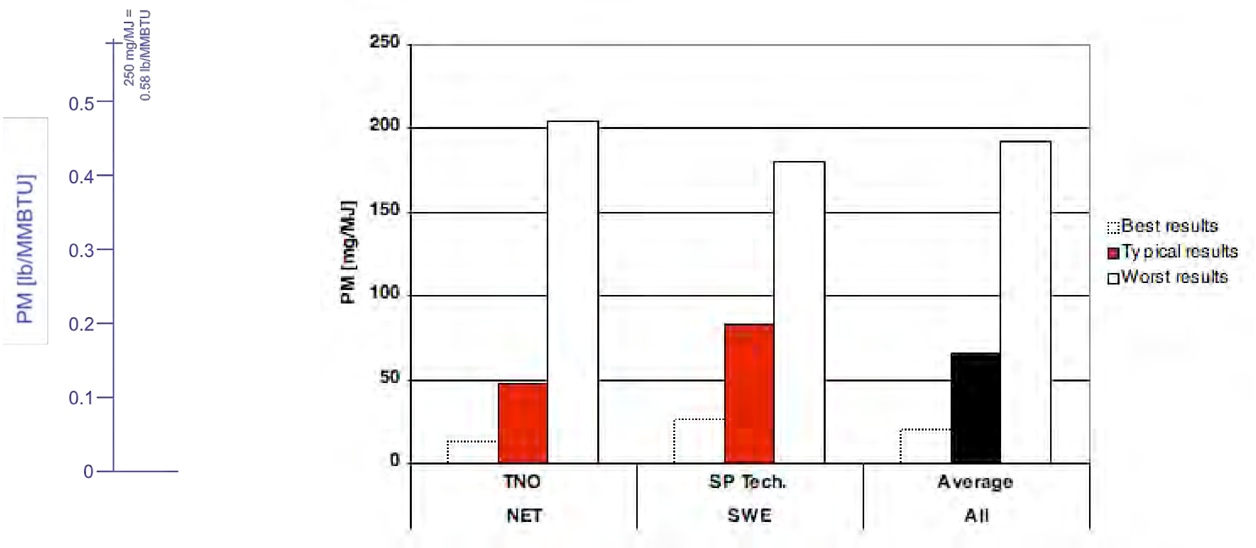

Figure 4.11 Emission factors for closed inset appliances

4.7.3 Wood stoves

Within the survey, most data was delivered for the category of wood stoves, therefore, this rubric represents a broad overview. For typical measured solid particles with start phase, the scope ranges from 64 to 87 mg/MJ (0.15 to 0.20 lb/MMBTU). Measurements with condensables and in dilution tunnel show persistently higher results, which range from 340 to 544 mg/MJ (0.79 to 1.26 lb/MMBTU).

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) (0.22 lb/MMBTU to 1.51 lb/MMBTU). 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) (0.22 lb/MMBTU to 1.51 lb/MMBTU).

The Finnish value is a revised number, which will apply soon, while currently the old value of 400 mg/MJ (0.93 lb/MMBTU) is still in use. 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 of 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 4.12 shows the emission factors for wood stoves with an indication of ranges from best, typical to worst type of operation or combustion type. Figure 4.13 summarizes the same data with indication of the typical data only.

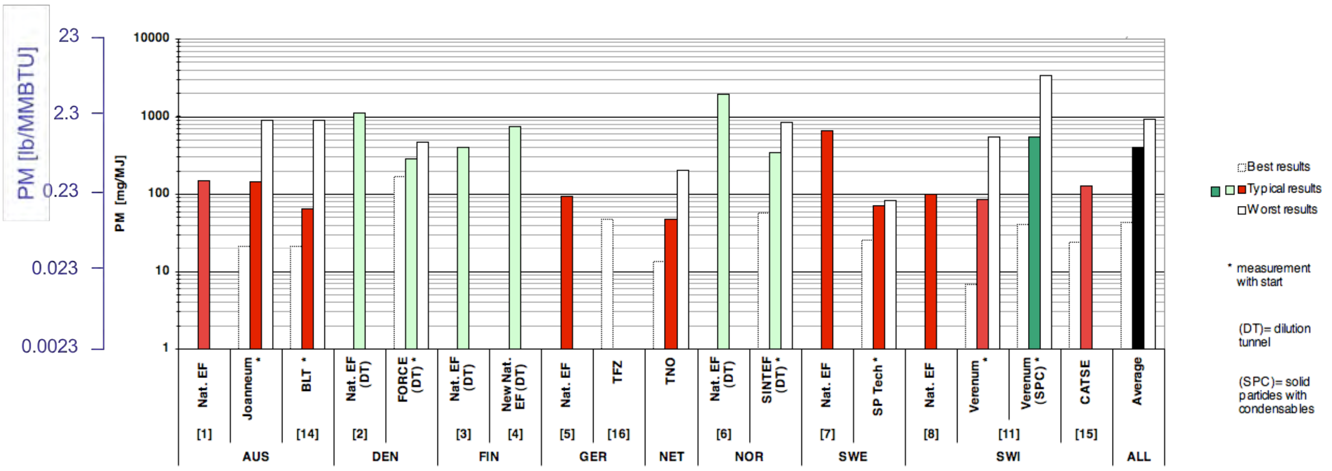

Figure 4.12 Range of emission factors from worst to best (where available) for wood stoves depending of type of operation and/or equipment

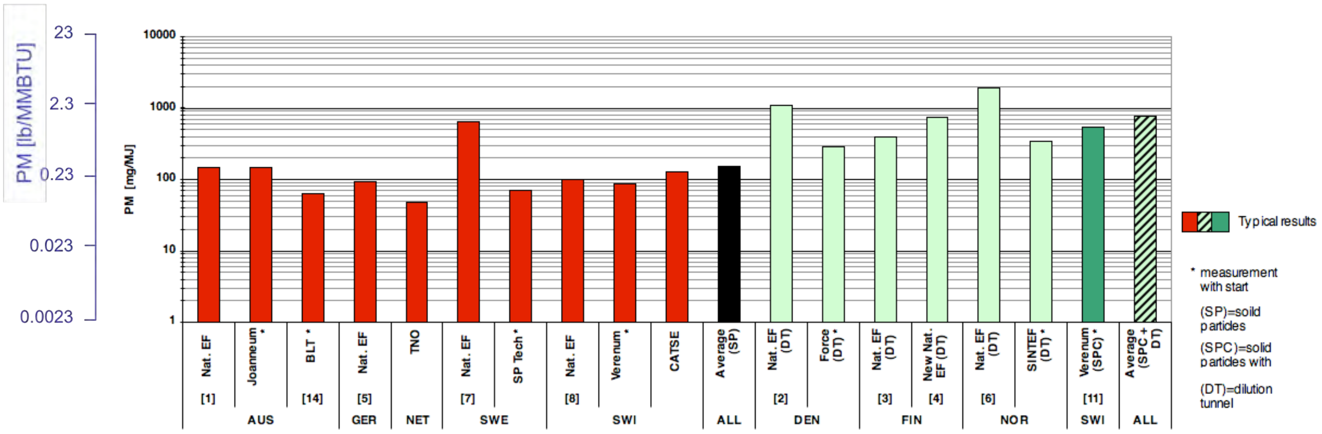

Figure 4.13 Average emission factors for wood stoves

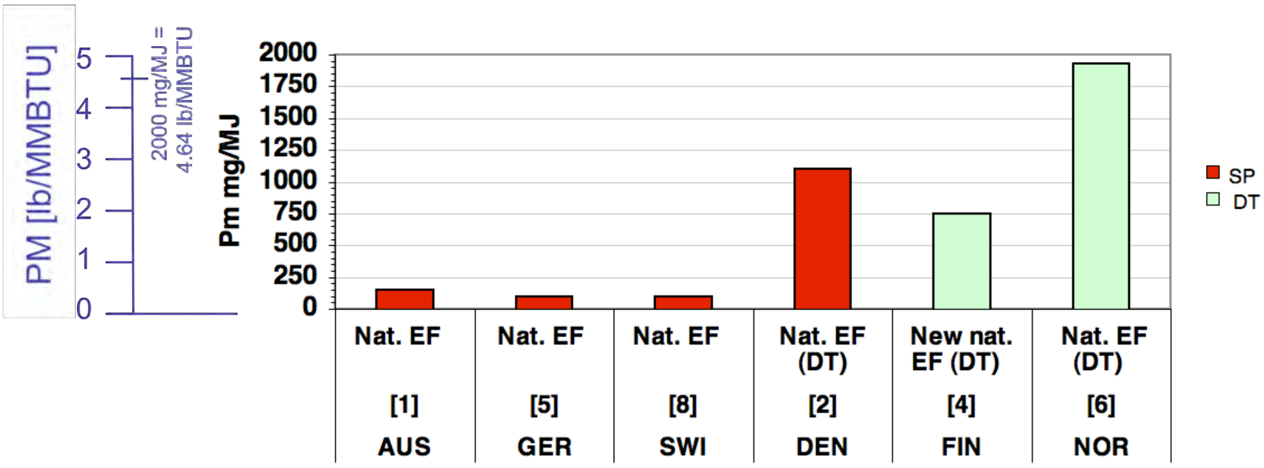

Figure 4.14 National emission factors for wood stoves

4.7.4 Log wood boilers

For log wood boilers, the technology of two-stage combustion has been implemented for more than 20 years. Most modern log wood boilers used 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 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, 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 4.15 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 4.16 shows emission data from log wood boilers with forced draft. Under typical operation conditions, boilers with downdraft principle allow significantly lower emissions than updraft boilers.

In addition to the combustion principle, the hydraulic implementation of the boiler in the heating system, and the application and management of a heat storage tank can significantly influence the emissions in practical operation. Figure 4.17 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 allows an operation at full load or at steady-state part-load with low emissions. On the other hand, boilers operated for house heating without heat storage tanks may be used with throttled air inlet, thus leading to excessively high emissions of uncombusted carbon and particles.

Figure 4.18 shows an overview of data from log wood boilers. No information about the combustion principle was available.

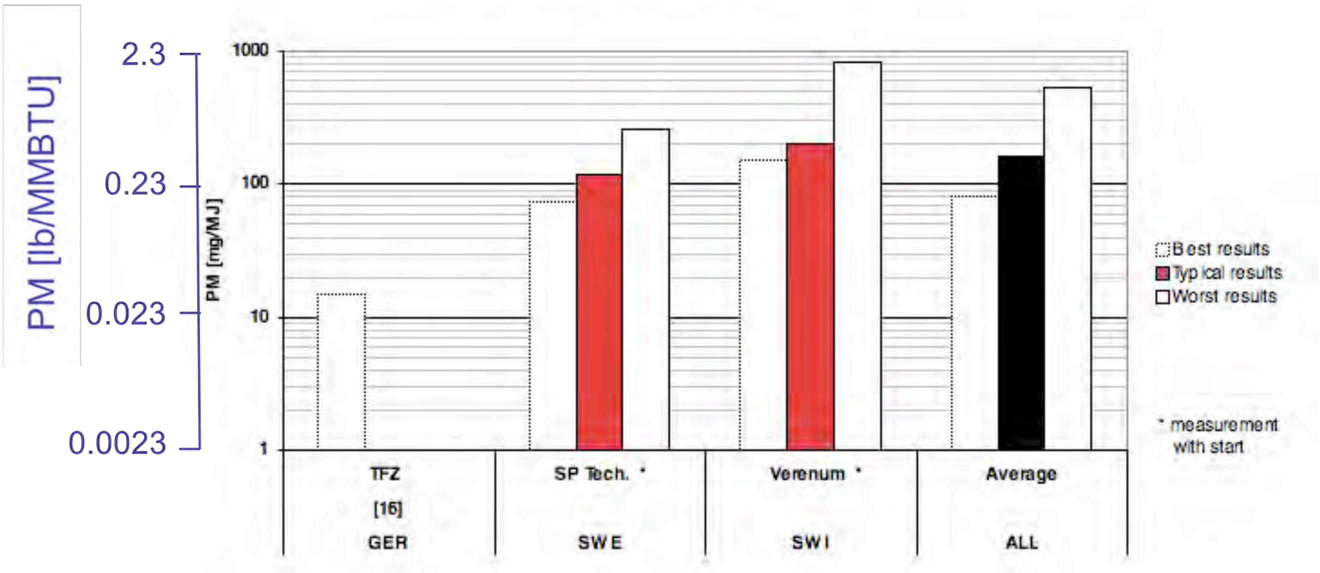

Figure 4.15 Range of emission factors from worst to best (where available) for log wood boilers with updraft combustion without ventilator

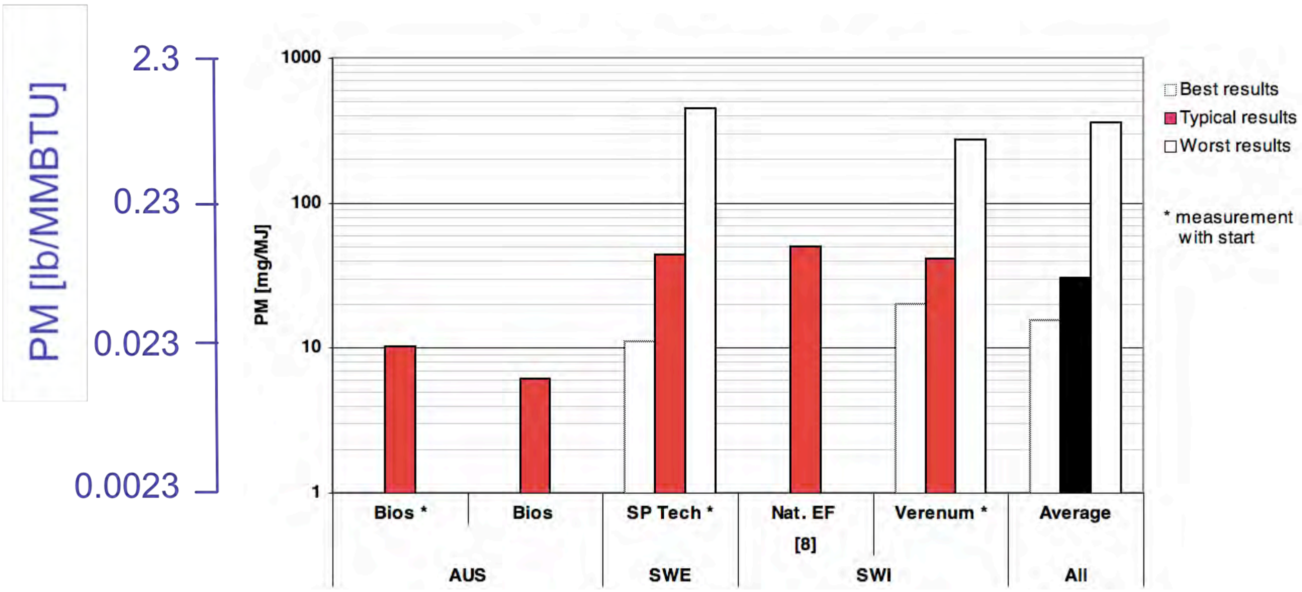

Figure 4.16 Range of emission factors from worst to best (where available) for log wood boilers with forced downdraft combustion

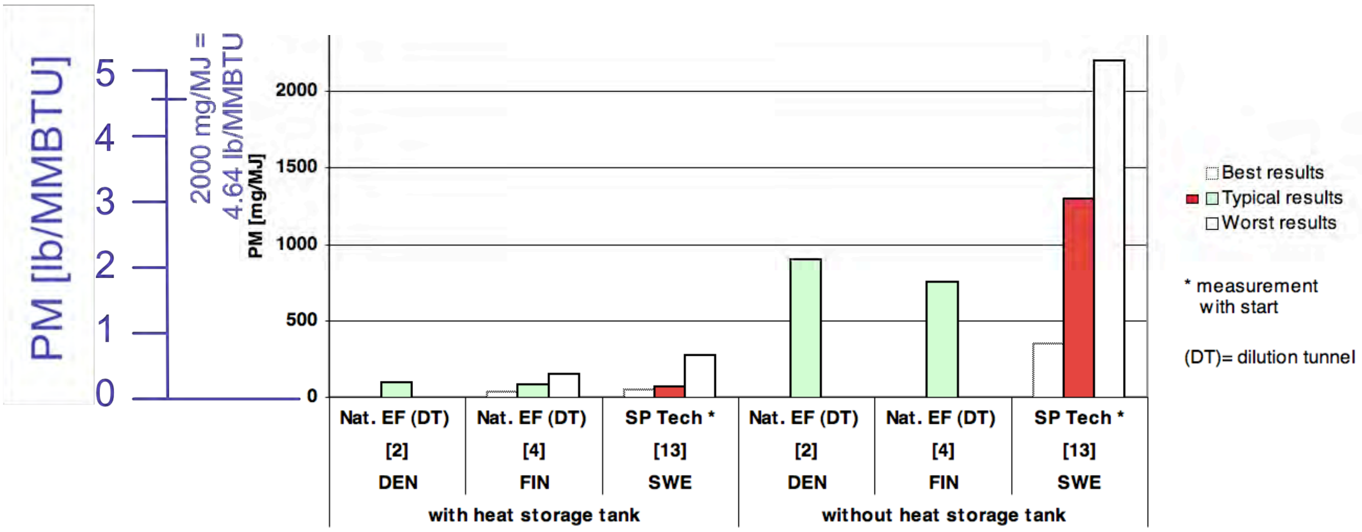

Figure 4.17 Emission factors for log wood boilers with and without heat storage tank

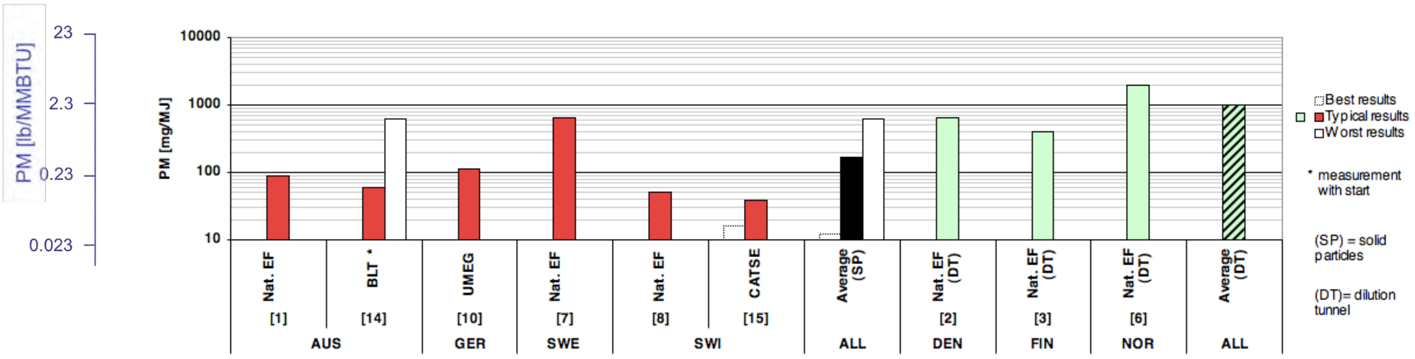

Figure 4.18 Emission factors for log wood boilers, where combustion type is not specified

4.7.5 Pellet stoves and boilers

Figure 4.19 and Figure 4.20 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 considered. The emission factors for pellet combustion are, in most cases, between 10 – 50 mg/MJ (0.023 – 0.116 lb/MMBTU) for typical operation and are comparable to the best results achieved by log wood combustion. If the 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 a magnitude lower, which is regarded as the main advantage of pellet combustion. However, many investigations have shown that the use of biomass other than wood, with low amounts of bark for pellet combustion, in residential heating appliances results in significantly increased emissions of particulate matter (typically by a factor of more than 3), as well as in emission of NO_X. The reported data are valid for wood pellets with low ash content only.

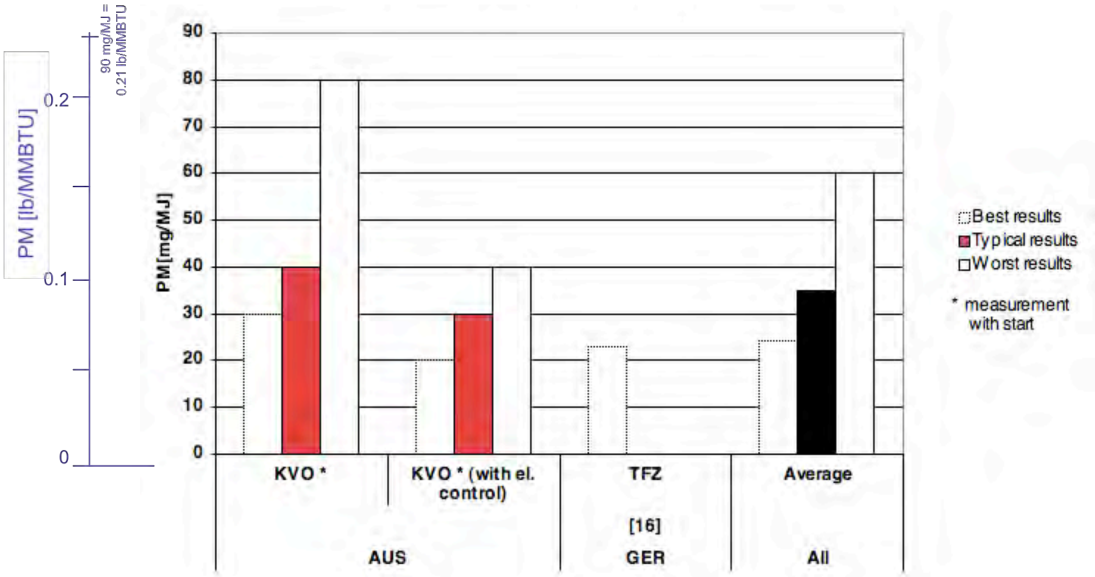

Figure 4.19 Range of emission factors from worst to best (where available) for pellet stoves with natural draft

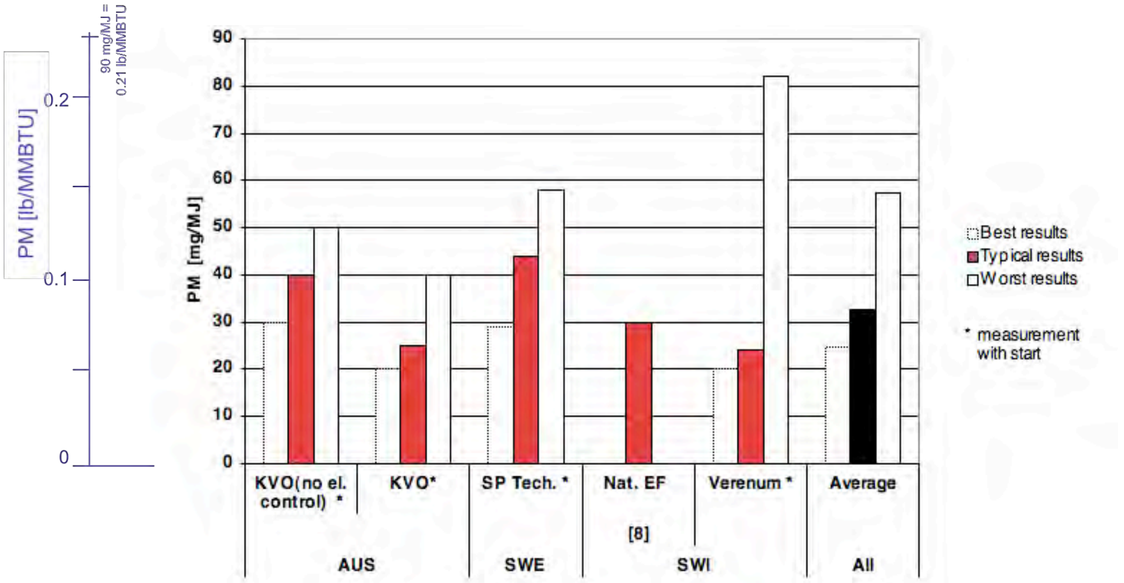

Figure 4.20 Range of emission factors from worst to best (where available) for pellet stoves with forced draft and electronic combustion control

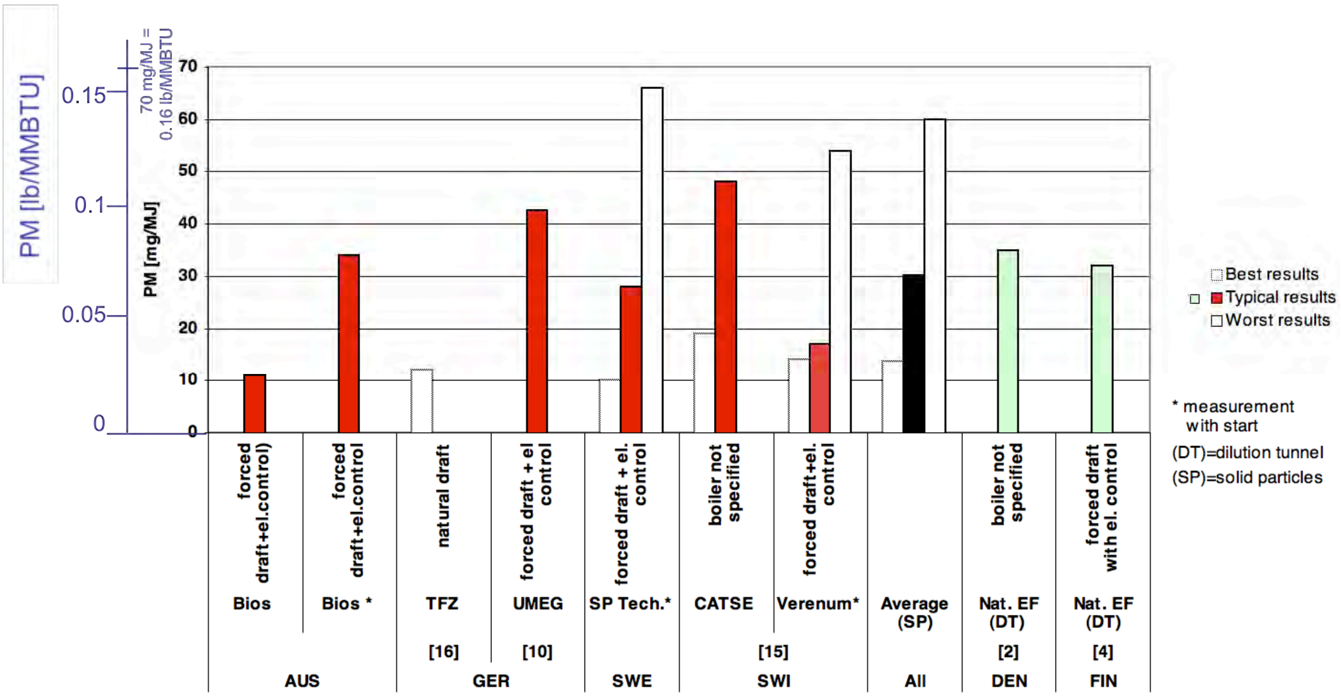

Figure 4.21 Range of emission factors from worst to best (where available) for pellet boilers

4.7.6 Overview on residential wood combustion

Figure 4.22 gives a summary of the average emission factors for pellet combustion, log wood boilers, and wood stoves.

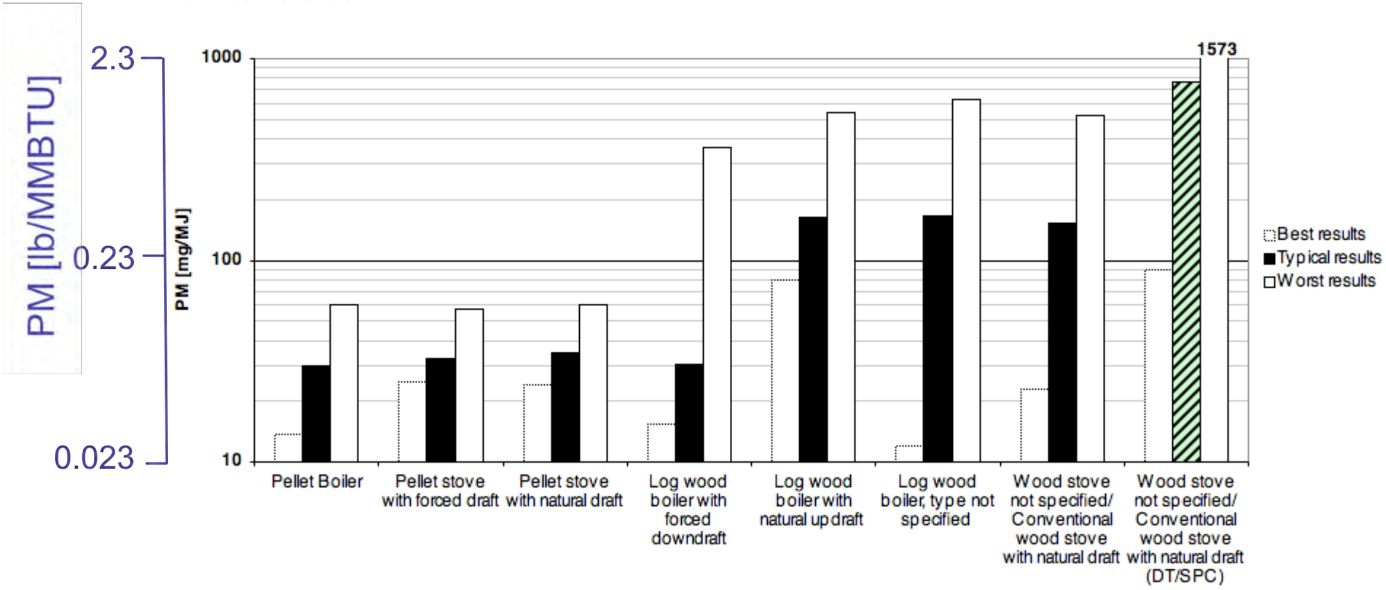

Figure 4.22 Average emission factors (best, typical, worst) for pellet boilers, pellet stoves, log wood boilers, and wood stoves - All data indicated as solid particles SP except for wood stoves, where data including condensables (SPC) or measured in dilution tunnel are given in the last column.

- 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 that 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 (0.070 lb/MMBTU). This is 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 might be underestimated. For downdraft boilers, an increase by a factor of 10 is expected under poor operation conditions. The main advantage of pellet combustion is that very poor operation is assumed to be very rare because of the homogeneous fuel and 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 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 small batches of small and dry logs, which lead to a constant and low heat output by continuous manual feeding in short periods and assumes an optimized 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 (0.35 lb/MMBTU) for solid particles.

- Similar values are expected for old-type wood boilers with natural updraft combustion. Two-stage combustion with forced draft is regarded as a significant improvement. However, the type of operation of log wood boilers in practice strongly depends on the hydraulic integration in the heating system. For conventional house heating, a combination with a heat storage tank is usually needed to avoid 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. A comparison of these data with measurements of solid particles reveals significantly higher average emission factors. Since the data shown in Figure 4.22 are derived from different investigations and different combustion devices, they do not allow a direct comparison between the different measurement methods. However, the significantly higher (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, since the data in Figure 4.22 do not allow a direct comparison of the sampling types.

4.7.7 Automatic biomass combustion plants

Figure 4.23 and Figure 4.24 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 range from 50 – 100 mg/MJ (0.12 – 0.23 lb/MMBTU), which is in line with the typical emission limit values valid today (e.g. 150 mg/m^3 at 11 or 13 Vol.-% O_2).

However, an investigation of field measurements in Switzerland for a large number of installations revealed a relatively broad range of emissions from 30 to 350 mg/MJ (0.070 to 0.81 lb/MMBTU), which demonstrates 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 4.25 and Figure 4.26. However, emission factors of installations in this category strongly depend on the type of flue gas cleaning and on the imposed emission limit values. In combustion plants greater than 500 kW in Switzerland[1], significant changes are expected. New emission limit values in this category will make the application of fine particle removal systems necessary in future and lead to a significant reduction of PM emissions.

For the comparison of different particle sources, it needs to be recognized that the presented emission factors are indicated as particle mass concentrations and do not respect the health relevance of different particle types. Particles and condensables found from wood burned under very poor combustion conditions, such as 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 staged design at good operation conditions consist mainly of salts. Consequently these particles exhibit far lower toxicity and carcinogenity [Klippel & Nussbaumer 2007].

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[1] 20 mg/m^3 at 11 Vol.-% O_2 are valid for plants > 1 MW from 9.1.07 instead of formerly 150 mg/m^3.
20 mg/m^3 at 13 Vol.-% O_2 are introduced for plants > 500 kW in 2008 instead of formerly 150 mg/m^3.

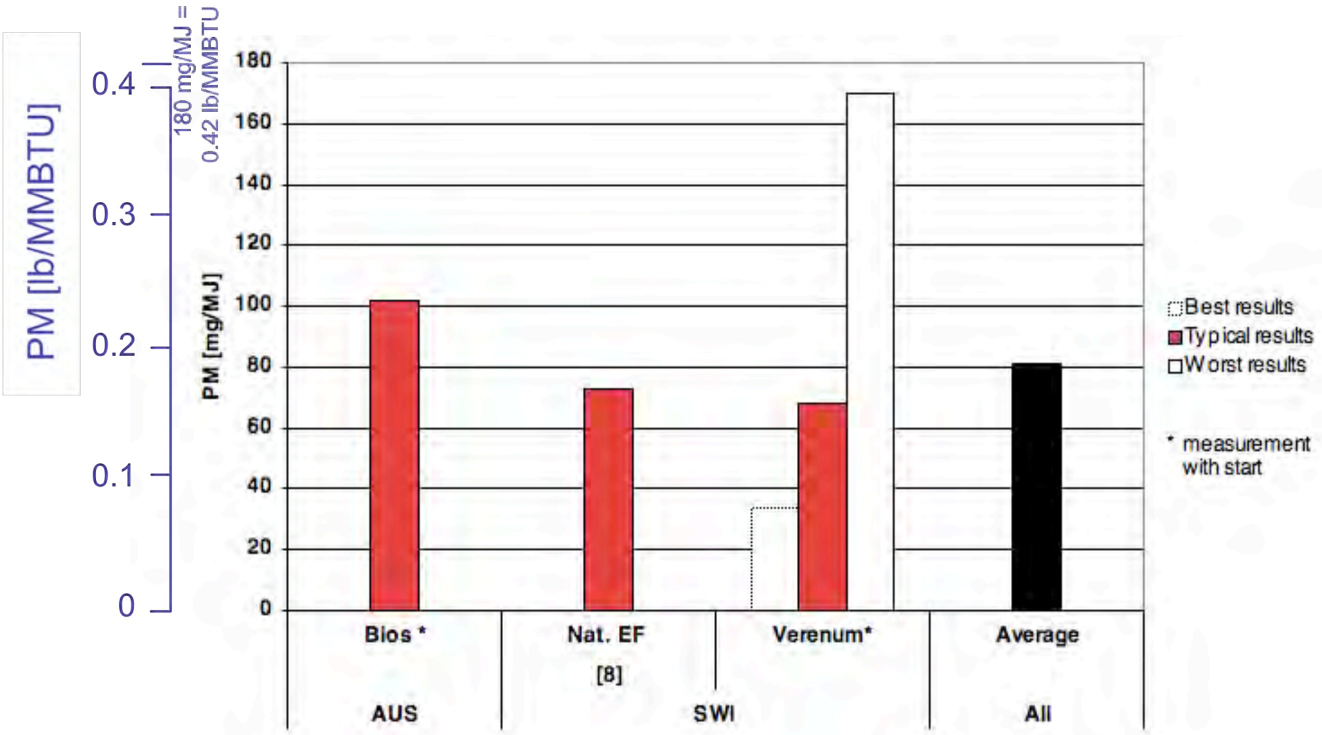

Figure 4.23 Emission factors for under stoker boilers from 70 – 500 kW

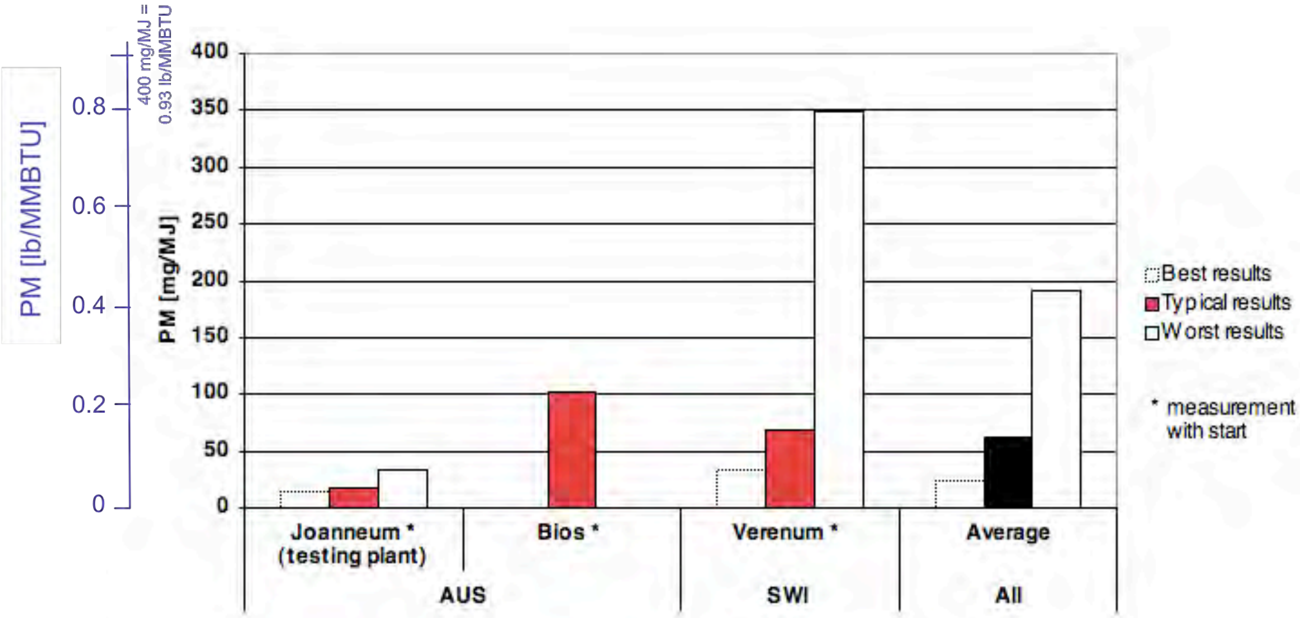

Figure 4.24 Emission factors for grate boilers from 70 – 500 kW

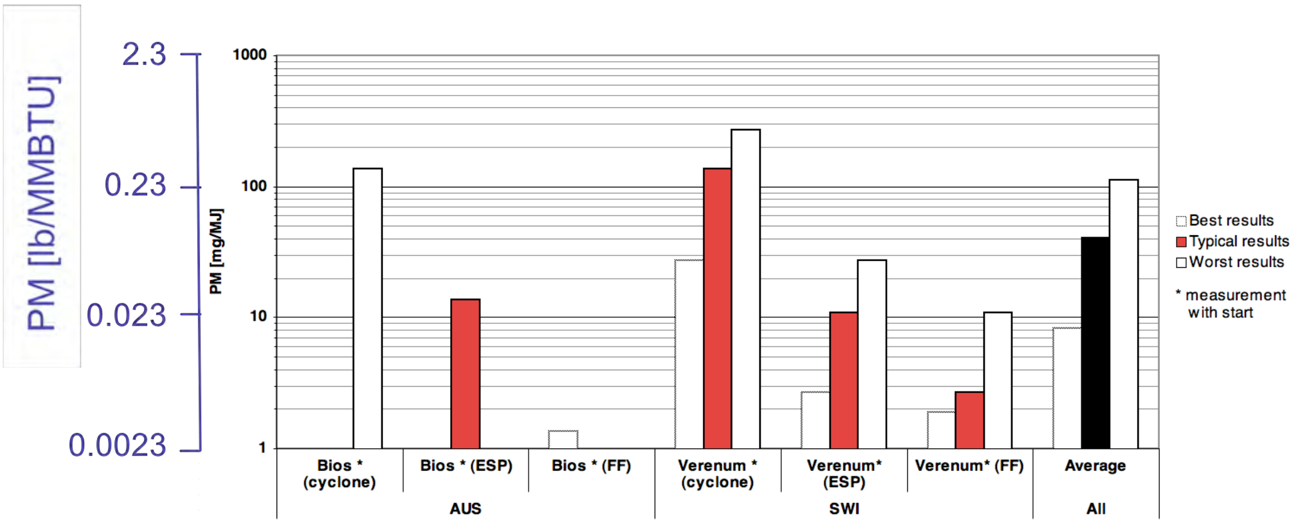

Figure 4.25 Emission factors for under stoker boilers from 500 kW – 10 MW

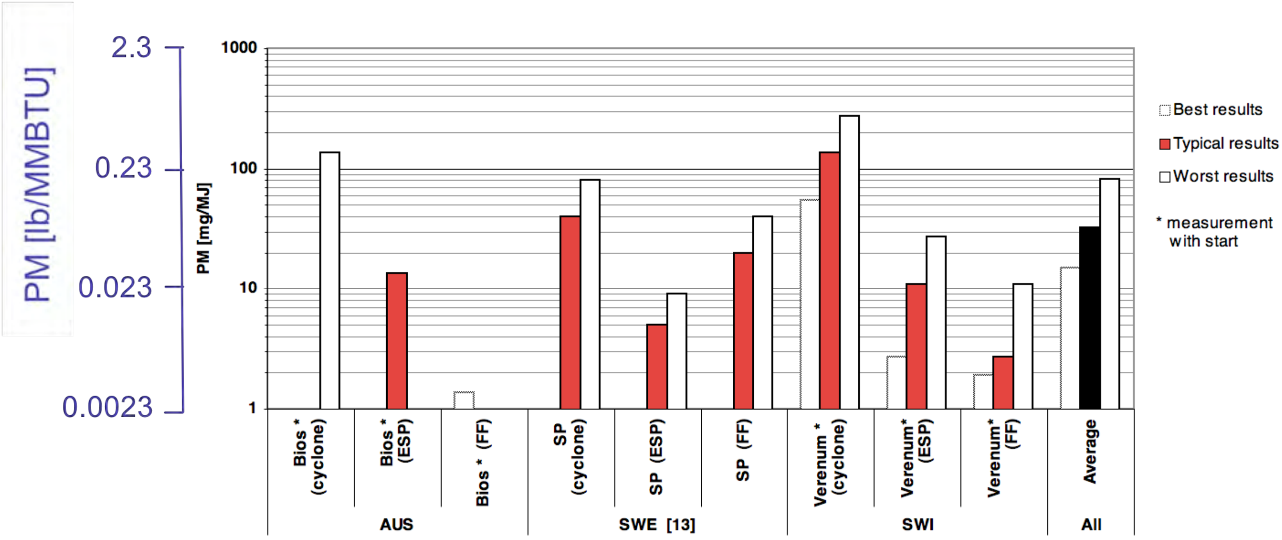

Figure 4.26 Emission factors for grate boilers from 500 kW – 10 MW

4.8 Particle sampling: Solid particles, condensables, dilution tunnel

For the emission factors from wood stoves, a limited number of data is available from Sweden. [Ryde and Johansson, 2007] 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 4.5. In addition, data is 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 4.27 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 4.28 illustrates the ratio of DT/SP, when measured in the dilution tunnel, and of SPC/SP when measured with condensables found in impingers. In one 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 one (≤ 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 three and six (Switzerland).

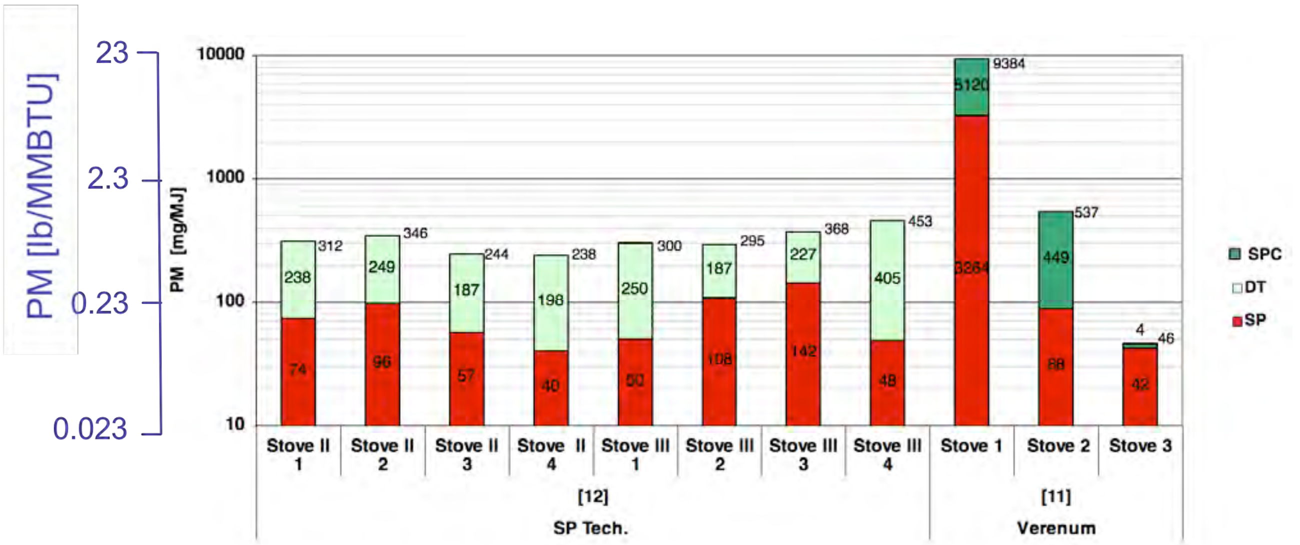

Figure 4.27 Comparison of PM emission factors on solid particles (SP), particles in dilution tunnel (DT), and solid particles plus condensables from impinger (SPC) for wood stoves

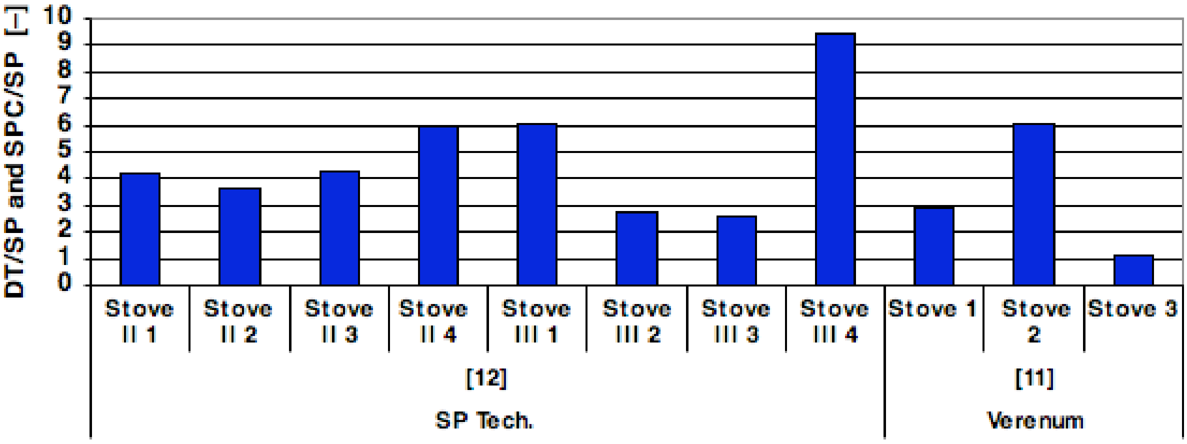

Figure 4.28 Ratio DT/SP and SPC/SP for wood stoves acc. to Figure 4.27

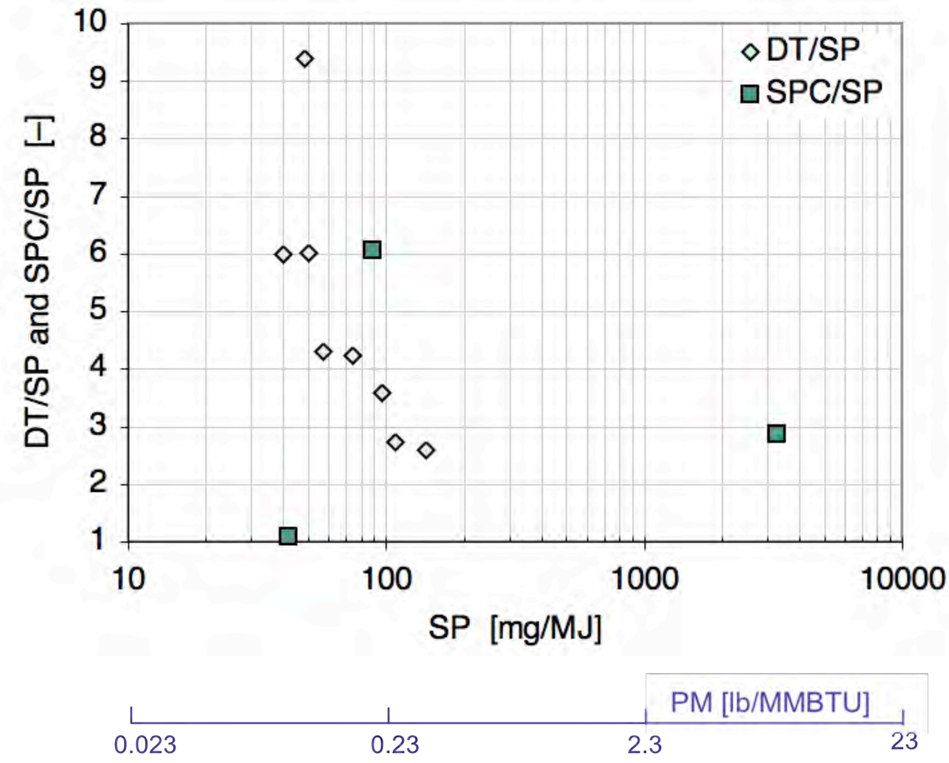

Figure 4.29 Ratio DT/SP and SPC/SP for wood stoves as function of SP

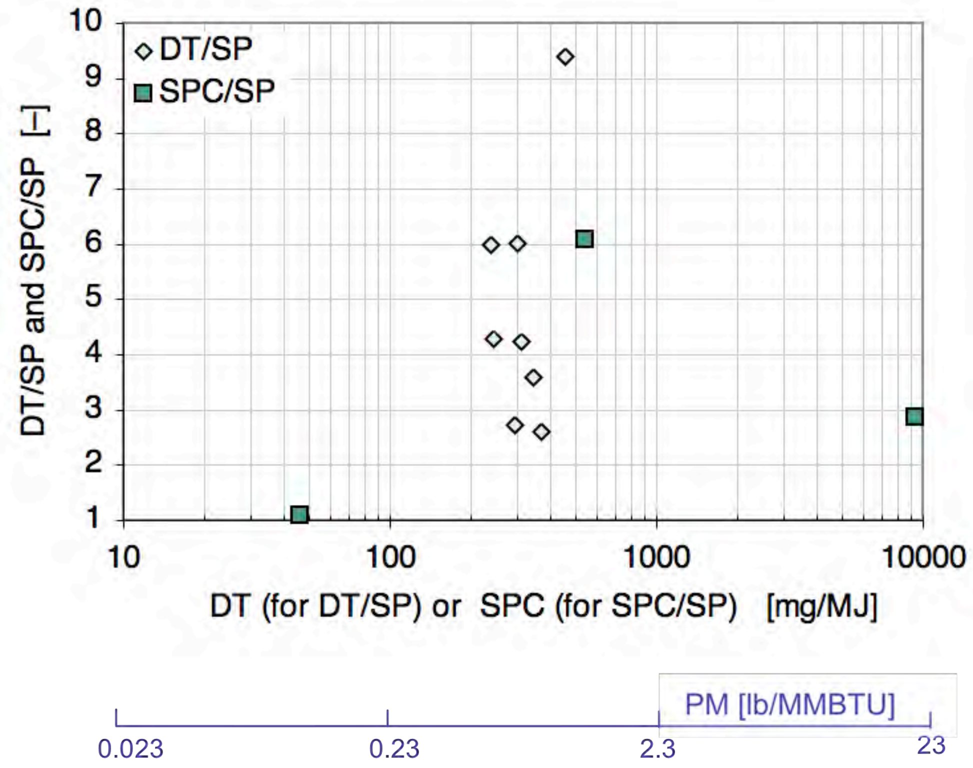

Figure 4.30 Ratio DT/SP and SPC/SP for wood stoves as function of SPC and DT, respectively

5 Norms and emission limit values

Europe

	Standard No.	Application
Boiler	CEN-303-5	Heating boilers for solid fuels, hand and automatically stocked, nominal heat output of up to 300 kW
	CEN-12809	Residential independent boilers fired by solid fuel, nominal heat output up to 50kW
Stove	CEN-14785	Residential space heating appliances fired by wood pellets
	CEN-12815	Residential cookers fired by solid fuel
	CEN-13229	Insert appliances including open fires fired by solid fuels
	CEN-13240	Room heaters fired by solid fuel
	CEN-14785	Residential space heating appliances fired by wood pellets
	CEN-15250	Slow heat release appliances fired by solid fuel

Norm	Titel / Inhalt
EN 12809	Heizkessel für feste Brennstoffe - Nennwärmeleistung bis 50 kW - Anforderungen und Prüfung
EN 12815	Herde für feste Brennstoffe - Anforderungen und Prüfung
EN 13229	Kamineinsätze einschliesslich offene Kamine für feste Brennstoffe - Anforderungen und Prüfung
EN 13240	Raumheizer für feste Brennstoffe - Anforderungen und Prüfungen
EN 13284	Emissionen aus stationären Quellen - Ermittlung der Staubmassenkonzentration bei geringen Staubkonzentrationen
EN 13384	Abgasanlagen - Wärme- und strömungstechnische Berechnungsverfahren
EN 13502	Abgasanlagen - Anforderungen und Prüfverfahren für Keramik-Aufsätze
EN 1443	Abgasanlagen - Allgemeine Anforderungen
EN 14785	Raumheizer zur Verfeuerung von Holzpellets - Anforderungen und Prüfverfahren
EN 18160	Abgasanlagen, teil 1-x
EN 1856	Abgasanlagen - Anforderungen an Metall-Abgasanlagen

EN 267	Ölbrenner mit Gebläse - Begriffe, Anforderungen, Prüfung, Kennzeichnung
EN 303	Heizkessel - Teil 1-x
EN 304	Heizkessel - Prüfregeln für Heizkessel mit Ölzerstäubungsbrennern
CEN TS 14588	Feste Biobrennstoffe - Terminologie, Definitionen und Beschreibungen; Deutsche Fassung CEN/TS 14588:2003
CEN TS 14774	Feste Biobrennstoffe - Verfahren zur Bestimmung des Wassergehaltes - Verfahren der Ofentrocknung
CEN TS 14775	Feste Biobrennstoffe - Verfahren zur Bestimmung des Aschegehaltes; Deutsche Fassung CEN/TS 14775:2004
CEN TS 14918	Feste Biobrennstoffe - Verfahren zur Bestimmung des Heizwertes; Deutsche Fassung CEN/TS 14918:2005
CEN TS 14961	Feste Biobrennstoffe - Brennstoffspezifikationen und -klassen; Deutsche Fassung CEN/TS 14961:2005
CEN TS 15103	Feste Biobrennstoffe - Verfahren zur Bestimmung der Schüttdichte; Deutsche Fassung CEN/TS 15103:2005
CEN TS 15104	Feste Biobrennstoffe - Verfahren zur Bestimmung des Gehaltes an Gesamtkohlenstoff, Wasserstoff und Stickstoff - Instrumentelle Verfahren; Deutsche Fassung CEN/TS 15104:2005
CEN TS 15105	Feste Biobrennstoffe - Verfahren zur Bestimmung des wasserlöslichen Gehaltes an Chlorid, Natrium und Kalium; Deutsche Fassung CEN/TS 15105:2005
CEN TS 15148	Feste Biobrennstoffe - Verfahren zur Bestimmung des Gehaltes an flüchtigen Substanzen; Deutsche Fassung CEN/TS 15148:2005
CEN TS 15234	Feste Biobrennstoffe - Qualitätssicherung von Brennstoffen; Deutsche Fassung CEN/TS 15234:2006
CEN TS 15289	Feste Biobrennstoffe - Bestimmung des Gesamtgehaltes an Schwefel und Chlor; Deutsche Fassung CEN/TS 15289:2006
CEN TS 15290	Feste Biobrennstoffe - Bestimmung von Hauptelementen; Deutsche Fassung CEN/TS 15290:2006
CEN TS 15296	Feste Biobrennstoffe - Analysenberechnung auf unterschiedliche Bezugsbasen; Deutsche Fassung CEN/TS 15296:2006
CEN TS 15297	Feste Biobrennstoffe - Bestimmung von Spurenelementen; Deutsche Fassung CEN/TS 15297:2006
prCEN TS 14918	Feste Biobrennstoffe - Verfahren zur Bestimmung des Heizwertes; Deutsche Fassung CEN/TS 14918:2005
VDI 2006	Messen von Partikeln - Staubmessungen in strömenden Gasen

Comparison of the standard structure in Europe and US

	Europe		USA	
	Heater	Boiler	Heater	Boiler
Description of the requirements	CEN 13240 CEN 12815 CEN-13229 CEN-14785 CEN-15250 CEN-15544(2)	CEN 303-5 CEN-12809	Subpart AAA(2)	-
Description of the test conditions			Method 28	Method 28 OWHH (project)
Description of the measurement method			Method 5H or 5G for particles(1)	Method 5H or 5G for particles(1)

OWHH = Outdoor wood fired hydronic heating appliances

(1): There are methods to measure other emissions, like CO, NOx, etc., but there are no limits fixed
(2): Depending on the type of heater - The difference is on the security requirements.
(3): EPA: 40 CFR Part 60 - Standard of Performance for New Stationary Sources (NSPS)
http://www.tceq.state.tx.us/permitting/air/rules/federal/60/60hmpg.html
http://www.epa.gov/epacfr40/chapt-I.info/

Different structure of standards and legislation for emission measurements in Europe and the United States:

➔ European standards refer to types of firing appliances. Standards generally include appliance requirements and test methods for emission measurements. Emission measurements include solide particles, CO, and partly VOC.

➔ Situation in the USA: Subpart AAA – (Standards of Performance for New Residential Wood Heaters) summarizes all conditions a wood heater has to satisfy, and the methods that have to be used for the certification (see §60.534, page 407). Method 28 determines how the wood stove has to be operated during the certification. How to conduct the measurements is defined in Method 5H (stack location) or 5G (dilution tunnel). Only particulate matter measurements are mandatory for a wood heater certification. Methods for NO_X, CO, SO_2 measurements exist but are not part of the certification process.

Test fuel requirements (wood)

		CEN 13240	CEN 303-5	EPA method 28	EPA method 28 OWHH
Wood humidity (wet basis)	min	12%	12%	16%	16%
	max	20%	20%	20%	20%
Wood size	Length	Manuf.(1)	Manuf.(1)	5/6*L(2)	0.8*L(2)
	width	Manuf.(1)	Manuf.(1)	4 in.	4 in.
	height	Manuf.(1)	Manuf.(1)	4 or 2 in.	4 in.
Wood type		Beech, Birch	Beech, Birch, oak, spruce	Douglas fir	Red or white oak
Wood amount pro charge		f(P)(3)	f1(V)(4)	f2(V)(5)	f2(V)(5)

(1) As specified by the manufacturer
(2) L: usable length of the firebox
(3) f(P) the amount of wood is a function of the output power of the wood heater
(4) f1(V) the amount of wood is the maximum which can be filled
(5) f2(V) the amount of wood is a function of the fire box volume

Sources: Wood humidity:

- CEN 13240 table B1, page 71
- CEN 303-5 table 8, page 17
- EPA method 28, section 7.1.2 page 1408
- EPA method 28 OWHH, section 12.2 page 10

Wood size

- CEN 13240: table B1, page 71
- CEN 303-5: table 8, page 17
- EPA method 28: section 7.1.4, page 1409 + fig 28.2 and 28.3, page 14.45
- EPA method 28 OWHH: section 12.2, page 10 + fig 1 page 25

Wood type

- CEN 13240: table B1, page 71
- CEN 303-5: section 5.3, page 16
- EPA method 28: section 7.1.1, page 1408
- EPA method 28 OWHH: section 12.2 page 10

Wood amount pro charge

- CEN 13240: A4.2, page 39
- CEN 303-5: section 5.7.4.1, page 19
- EPA method 28: section 8.8.4, page 1417
- EPA method 28 OWHH: section 12.2.3, page 12

Chimney

	Europe		USA	
	Heater	Boiler	Heater	Boiler
	CEN 13240	CEN 303-5	EPA method 28	EPA method 28 OWHH
Chimney length	-	-	4.6m(1)	4.6m(1)
Chimney isolation	Insulated	Insulated	Half insulated	Half insulated
Chimney draught	Forced(2)	Forced(2)	Natural(3)	Natural(4)

(1) Measured from the ground - Has to be isolated from 2.6 m to the top
(2) Either to value specified by manufacturer, or to values specified in the standard
(3) Natural, but a ventilator can be installed. The draft created shall not be greater than 1.25 Pa (the temperature is specified)
(4) No details found

Sources: Chimney length:

- CEN 13240:
- CEN 303-5:
- EPA method 28: section 6.11.1, page 1406
- EPA method 28 OWHH: section 9.1.2, page 7

Chimney draught:

- CEN 13240: section 6.4, figure 1 page 24
- CEN 303-5: section 4.2.3, page 16, and figure 2, page 17
- EPA method 28: section 6.12.3, page 1407
- EPA method 28 OWHH: section 9.1.2, page 7

Heat extraction

	Europe		USA	
	Heater	Boiler	Heater	Boiler
	CEN 13240	CEN 303-5	EPA method 28	EPA method 28 OWHH
Temperature input	?	$T_{in} = T_{out} - T_{diff}$ $10°K < T_{diff} < 25°K$	-	?
Temperature output	$75°C < T_{out} < 85°C$	$70°C < T_{out} < 90°C$	-	?
Water discharge	constant	constant	-	constant

Sources:

- CEN 13240: section A.2.5, page 38
- CEN 303-5: section 5.8.2, page 19
- EPA method 28: -
- EPA method 28 OWHH: section 12.5.1, page 13

Operation mode

			Europe		USA	
			Heater	Boiler	Heater	Boiler
			CEN 13240	CEN 303-5	EPA method 28	EPA method 28 OWHH
Operating charges		1 min. charge	Q_{min}=0.25*$P_n$$^{(1)}$	Q_{min}=0.3*$P_n$$^{(2)}$	Q_{min}< 4 kW (*)	Q_{min}=0.15*$P_n$$^{(1)}$
		2	-	-	$P_{2\ min}$= 4 kW $P_{2\ max}$= 6.25 kW (**)	$P_{2\ min}$=0.16*$P_n$$^{(1)}$ $P_{2\ max}$=0.24*$P_n$$^{(1)}$
		3	-	-	$P_{3\ min}$ = 6.25 kW $P_{3\ max}$= 9.5 kW(***)	$P_{3\ min}$ =0.25*$P_n$$^{(1)}$ $P_{3\ max}$ =0.50*$P_n$$^{(1)}$
		4 max. charge	$P_n$$^{(1)}$	$P_n$$^{(1)}$	P_{max}	$P_n$$^{(1)}$
Batch			f(P)$^{(3)}$	f1(V)$^{(4)}$	f2(V)$^{(5)}$	f2(V)$^{(5)}$
Batch length	Operating mode 4	Pretest	Yes	Yes	Yes	Yes
		Start	On charcoal bed 50g	On charcoal bed, when operating temperature is reached, at least 6 hrs	On charcoal bed 20-25% of M$^{(6)}$	On charcoal bed 10-20% of M$^{(6)}$
		Charge adjustment	?	No (only during the pretest)	Max once per batch$^{(8)}$	Max once per batch$^{(8)}$
		End	M$^{(6)}$=0	M$^{(6)}$=0	M$^{(6)}$=0	M$^{(6)}$=0
	Operating modes 1-3	Pretest	Yes	Yes	Yes	Yes
		Start	On charcoal bed	On charcoal bed, when operating temperature is reached at least 6 hrs	On charcoal bed 20-25% of M$^{(6)}$	On charcoal bed 10-20% of M$^{(6)}$
		Charge adjustment	?	No (only during the pretest)	Max once per batch$^{(8)}$	Max once per batch$^{(8)}$
		End	$t_{min}$$^{(7)}$	M$^{(6)}$=0	M$^{(6)}$=0	M$^{(6)}$=0

(1) Qn is the nominal heat output, as specified by the manufacturer

(2) If this heat output can not be reached, it has to be specified by the manufacturer

(3) f(Q_n) the amount of wood is a function of the heat output of the wood heater

B_{fl} = 360 000 * Q_n * t_b / (H_u*η)

B_{fl} = fuel mass (Brennstoffaufgabe) in kg)

t_b = minimum time of one batch or time of one batch as specified by manufacturer

f1(V) the maximum amount of wood that can be filled

(4) f2(V) the amount of wood is a function of the fire box volume. The shape of the test fuel crib shall be geometrically similar to the shape of the firebox volume. The test fuel density shall be 112+- 11.2 kg/m^3(w.w.) of usable firebox volume.

(5) The mass of the wood charge

(6) Minimum time, as specified by manufacturer, or as prescribed in standard

(7) Once per Batch, after 60% of the wood has been consumed

(*) Original is: 0.8 kg/h converted to power using a heating value of 18000 kJ/kg. If a wood heater cannot be operated at a burn rate below 0.8 kg/hr, two test runs shall be conducted with burn rates within Cat. 2

(**) Original is: 0.8 – 1.25 kg/h converted to power using a heating value of 18000 kJ/kg

(***)Original is: 1.25 – 1.9 kg/h converted to power using a heating value of 18000 kJ/kg

Sources: Operating charges

- CEN 13240:
  - Min charge: section A4.8.2 page 43
  - Max charge : section A4.7.2, page 42
- CEN 303-5:
  - Min charge: section 4.2.5 page 14
  - Max charge : section 5.8.2, page 19
- EPA method 28: section 8.1.1, page 1410
- EPA method 28 OWHH: section 4.3, page 5

Batch length

- CEN 13240:
  - Pretest A4.7.2, page 41 and A.4.8.2, page 43
  - Start A.4.7.3, page 42 and A.4.8.2, page 43
  - End A.4.7.3, page 42 and A.4.8.2, page 43
- CEN 303-5:
  - Pretest: section 5.7.4.1, page 19
  - Start: section 5.7.4.1, page 19
  - Charge adjustment: section 5.7.1, page 18
  - End: section 5.7.4.1, page 19
- EPA method 28:
  - Pretest: section 8.11.1, page 1420
  - Start: section 8.12.1, page 1420
  - Charge adjustment: section 8.12.3, page 1425
  - End: section 8.13, page 1426
- EPA method 28 OWHH:
  - Pretest: section 12.4.1, page 12
  - Start: section 12.4.2, page 13
  - Charge adjustment: section 12.5.2, page 14
  - End: section 12.5.3, page 14

Test duration

EN 303-5:

1) Boiler with manual fuel feeding
   - PM only at full load: 2 charges (including re-filling second batch), discontinuous
   - CO, OGC, CO2/O2 also at minimum heat output, one batch, continuous (20 sec.)
   - Boiler with automatic fuel feeding
   - PM only at full load during whole testing period, discontinuous
   - CO, OGC, CO2/O2 also at minimum heat output, one batch, continuous

CEN 13240:

2) Zeitbrand-Feuerstätte = Room heater for short heating periods, i.e., minimum 0.75 h at full load if operated with wood:
   - CO, CO2/O2 at full load, 0.75 h, 3 batches, continuous (1 min) (A.4.7.1, s.41)
3) Dauerbrand-Feuerstätte = Room heater for short heating periods, i.e., minimum 1.5 h at full if operated with wood:
   - CO, CO2/O2 at full load, 1.5 h, 2 batches, continuous (1 min) (A.4.7.1, s.41)

Method 28:

Duration of emission sampling is two hours. End the test run when the scale has indicated a test fuel charge weight of 0.00 kg or less for 30 seconds (s. 1427).

Test Method 28 OWHH:

Data are recorded at intervals of 10 min or less (12.5.1, s.13). The test run is ended when the scale has indicated a test fuel charge weight of 0.00 kg or less for 30 seconds.

Measurements

Summary of the measures that have to be performed during standardization

		Europe		USA			
		Heater	Boiler	Heater	Boiler	Heater	Boiler
		CEN 13240	CEN 303-5	EPA 28	EPA 28 OWHH	EPA 28	EPA 28 OWHH
				5-G	5-H	5-G	5-H
Efficiency		yes	yes	-	yes	-	yes
O_2		yes	yes	-	-	-	-
CO		yes	yes	-	-	-	-
NO_X		-	optional	-	-	-	-
VOC		-	yes	-	-	-	-
Particle sampling		chimney	chimney	dilution tunnel	chimney	dilution tunnel	chimney
Particles	Solid	–	at 180°C	at < 32°C	at < 120°C	at < 32°C	at < 120°C
	Cond.	–	–	–	at < 20°C	–	at < 20°C

Sources:

- CEN 13240: §6.2, page 23, and §A3, page 38
- CEN 303-5 §5.9.1, page 19
- For EPA: §6.534, page 407 of Subpart AAA
- EPA method 28 OWHH §9.1.1.5.1, page 8

Measurements methods

1. The efficiency

The wood heater efficiency can principally be measured in two ways:

- A direct method, where the energy output of the wood heater is directly measured. In the case of wood stoves, this is done with the help of a calorimeter room, and in the case of a wood boiler by measuring the energy output in the water.
- An indirect method, where the gaseous heat losses, both thermal and chemical, are measured.

		Europe		USA	
		Heater	Boiler	Heater	Boiler
		CEN 13240	CEN 303-5	EPA method 28	EPA method 28 OWHH
Efficiency		indirect	direct	-	direct

2. The emissions

Two types of measurments can be used:

- Directly in the stack
- In a dilution tunnel

Both Europe and United States use the method of measuring directly in the stack, with the exception of method 5G. The ISO project is to measure all the emissions in a dilution tunnel.

Emission limit values

Europe

European emission limit values according to EN 303-5

[mg/m^3] at 10% O_2

Qn	**Fuel feeding**	**CO**		
		class 1	class 2	class 3
Qn < 50 kW	manual	25000	8000	5000
50 < Qn < 150 kW	manual	12500	5000	2500
150 < Qn < 300	manual	12500	2000	1200
Qn < 50 kW	automatic	15000	5000	3000
50 < Qn < 150 kW	automatic	12500	4500	1250
150 < Qn < 300	automatic	12500	2000	1250
Qn	**Fuel feeding**	**PM10**		
		class 1	class 2	class 3
Qn < 50 kW	manual	2000	300	150
50 < Qn < 150 kW	manual	1500	200	100
150 < Qn < 300	manual	1500	200	100
Qn < 50 kW	automatic	1750	200	100
50 < Qn < 150 kW	automatic	1250	150	80
150 < Qn < 300	automatic	1250	150	80
Qn	**Fuel feeding**	**OGC**		
		class 1	class 2	class 3
Qn < 50 kW	manual	200	180	150
50 < Qn < 150 kW	manual	200	180	150
150 < Qn < 300	manual	200	180	150
Qn < 50 kW	automatic	200	180	150
50 < Qn < 150 kW	automatic	200	180	150
150 < Qn < 300	automatic	200	180	150

Note that some European countries have individual standards:
Switzerland, Austria, Germany. The standards are mostly more strict than class 3.

European emission limit values for heating boilers according to CEN 303-5 (A. 4.2.6., p.14)

Europe	**CO**			**PM**			**OGC**		
	class 1	**class 2**	**class 3**	**class 1**	**class 2**	**class 3**	**class 1**	**class 2**	**class 3**
Manual feeding	mg/MJ	mg/MJ	mg/MJ	mg/MJ	mg/MJ	mg/MJ	mg/MJ	mg/MJ	mg/MJ
< 50 kW	12250	3920	2450	98	88	74	980	147	74
50 – 150 kW	6125	2450	1225	98	88	74	735	98	49
150 – 300 kW	6125	980	588	98	88	74	735	98	49
Manual feeding	mg/MJ	mg/MJ	mg/MJ	mg/MJ	mg/MJ	mg/MJ	mg/MJ	mg/MJ	mg/MJ
Qn – 50 kW	7350	2450	1470	98	88	74	858	98	49
150 – 300 kW	6125	2205	613	98	88	74	613	74	39
150 – 300 kW	6125	980	613	98	88	74	613	74	39

1 mg/MJ = 1.055 g/MMBTU = 0.00232 lb/MMBTU

Switzerland, Germany, Austria, Norway

1 mg/MJ = 1.055 g/MMBTU = 0.00232 lb/MMBTU

Switzerland OAPC (LRV), from 1.1.2008		**CO**	**PM**	**OGC**
Appendix 3	Wood combustion	mg/MJ	mg/MJ	mg/MJ
< 70 kW		2720		
70 – 500 kW		680	102	
0.5 – 1 MW		340	14	
1 – 10 MW		135	11	
> 10 MW		81	5	27
Appendix 4	Type test for wood heating devices			
manual	Log wood boiler	544	41	
automatic	Wood chip boiler	272	61	
automatic	Pellet boiler	204	41	
manual	Room heater	1020	68	
automatic	Pellet room heater	340	34	
manual	Hearth	2040	75	
manual	Hearth for central heating	2040	102	
manual	Chimney	1020	68	

orignial values in [mg/m3, 13 Vol.-% O2]

Switzerland LRV, from 1.1.2012		**CO**	**PM**	**OGC**
Appendix 3	Wood combustion	mg/MJ	mg/MJ	mg/MJ
< 70 kW		2720		
70 – 120 kW		340	68	
120 – 500 kW		340	34	
0.5 – 1 MW		340	14	
1 – 10 MW		135	11	
10 MW		81	5	

orignial values in [mg/m3, 13 Vol.-% O2]

Switzerland LRV, from 1.1.2012		**CO**	**PM**	**OGC**
Appendix 4	Type test for wood heating devices	mg/MJ	mg/MJ	mg/MJ
manual	Log wood boiler	544	34	
automatic	Wood chip boiler	272	41	
automatic	Pellet boiler	204	27	
manual	Room heater	1020	51	
automatic	Pellet room heater	340	27	
manual	Hearth	2040	61	
manual	Hearth for central heating	2040	82	
manual	Chimney	1020	51	

orignial values in [mg/m3, 13 Vol.-% O2]

Austria		**CO**	**PM**	**OGC**	**NOx**
Quelle: EN 303-5 Anhang A1		mg/MJ	mg/MJ	mg/MJ	mg/MJ
manual	Boilers for biofuels	1100	60	80	150
automatic	Boilers for biofuels	500	60	40	150

Germany		**CO**	**PM**
EN 303-5 Appendix A2		mg/MJ	mg/MJ
< 50 kW	Wood boiler	2720	
50 – 150 kW		1360	102
150 – 500 kW		680	102
> 500 kW		340	102

orignial values in [mg/m3, 13 Vol.-% O2]

				EPA
Germany		**CO**	**PM**	**PM**
1. BImSchV, 2003		mg/MJ	mg/MJ	mg/MJ
Step 1: 3 mths aft. publ.	Room heater flat	1080	54	300
> 8 kW	Room heater full	1350	54	
	Room heat w. heat storage	1080	54	
	Chimney inlets	1080	54	
	Room heater flat	1080	54	
	Room heater full	1350	54	
	Stove	1080	54	
	Hearth	1620	54	
	Hearth with central h.	1890	54	
	Pellet stove	135	27	
Step 2: after 31.12.14	Room heater flat	540	11	300
> 8 kW	Room heater full	540	11	
	Room heat w. heat storage	540	11	
	Chimney inlets	540	11	
	Room heater flat	540	11	
	Room heater full	540	11	
	Stove	540	11	
	Hearth	540	11	
	Hearth with central h.	540	11	
	Pellet stove	81	5	
Step 1: 3 mths aft. publ.	Wood boiler > 4 - 500 kW	540	32	
	Wood boiler > 500 kW	324	32	
Step 2: after 31.12.14	Wood boiler > 4 kW	216	11	

Comparison of PM standards in Europe and USA

For log wood boilers, there are no emission limit values by EPA, while EPA method 28 is valid for room heaters and describes limit values on PM. However, a direct comparison between limit values according to EPA method 28 with standards in Germany, Switzerland, and Austria is not possible due to different sampling procedures and complex averaged weighing of emission data. To enable an indicative comparison, a fictitious example for EPA method 28 is given below. However, according to EPA, the difference caused by different sampling that may lead to higher PM data due to condensables, is not considered.

Quelle: EPA Subpart AAA			EPA Method 28				example	
USA	**PM**	**MJ/kg**	**kg/h**	**kg/h**	**kg/h**	**kg/h**	for comp.	
Quelle: EPA Subpart AAA	Average	18.3	0.8	1.25	1.9	3	Average	**Average**
	g/h		mg/MJ	mg/MJ	mg/MJ	mg/MJ	mg/MJ	**mg/MJ**
Catalytic stove	**4.1**		280	179	118	75	163	**160**
Non-catalytic stove	**7.5**		512	328	216	137	298	**300**
Non-catalytic stove at Qmin	**15**		1025	656	431	273	596	**600**

		Min	Max
cat 1	<	0.8	
cat 2	<	0.8	1.25
cat 3	<	1.25	1.9
cat 4	<	max.	

The following figures illustrate the emission limit values for CO and PM.

Comparison of CO and PM emission limits for **boilers**

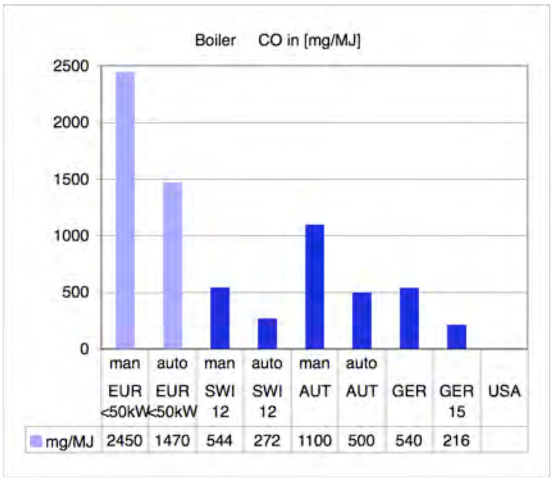

Fig. 1a Emission limit value on CO - There is no limit value for CO for boilers in the United States.

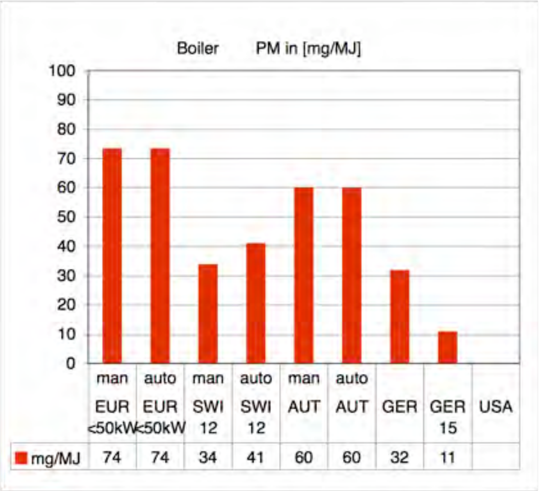

Fig. 1b Emission limit value on PM - There is no limit value for PM for boilers in the United States.

Comparison of CO and PM emission limits for **room heaters**

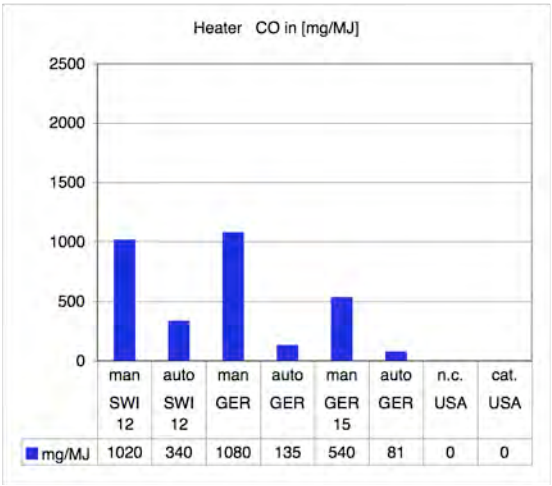

Fig. 2a Emission limit value on CO - There is no limit value for CO for room heaters in the United States.

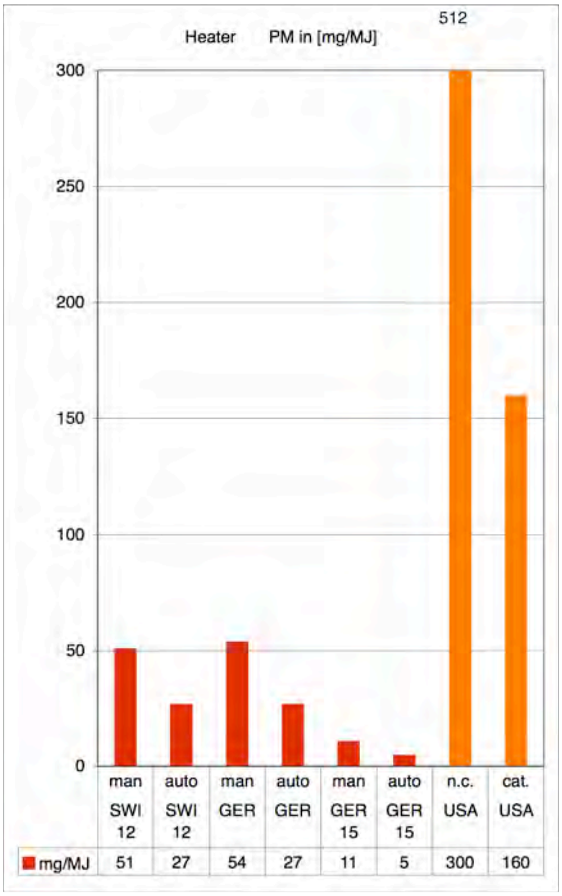

Fig. 2b Emission limit value on PM for room heaters, according to the fictitious example described above, which does not consider the different sampling in the United States.

6 Research activities in Europe

6.1 Overview

A large number of institutions are involved in research activates in biomass conversion, biofuel production, and related issues. Many topics such as pollutant formation are being investigated by research institutes with interest in combustion processes, where biomass is often one fuel among others. For example, combustion modeling is widely applied as a design tool for large combustion plants such as coal-fired power stations. Institutions involved in such activates have also focused on biomass, due to an increasing interest in renewable energies.

An overview on research institutions and industry involved in bioenergy in Europe can be found in the proceedings of the "European Biomass Conference & Exhibition", which is held every one and a half to two years. The latest conference was held in Berlin in 2007, while the next one will be held in Valencia, Spain in June 2008. Further information is available on the homepage:

http://www.conference-biomass.com

The conference attracts approximately 1500 participants from more than 70 countries, with a significant participation of 5% from the United States and Canada (Figure 6.1). Germany is by far the most important country with respect to total delegate number, while the Netherlands, Austria, Sweden, and Finland have an over proportional participation in comparison to their population. This reflects the important role of biomass in the nordic countries (pulp and paper industry) and in Austria (wood industry), while the Netherlands show an increasing interest in biomass to substitute imported coal. Roughly 50% of the conference topics cover contributions from policies and markets to biomass resources, while roughly 50% are related to research (Figure 6.2). Main research topics include: thermochemical conversion, biological conversion, and conversion to liquids. Biofuels have gained a great interest in the past 10 years due to significant funding and promoting by the European Commission. Due to funding of biofuels, many research institutions have focused their activities on fuel production with a decreasing interest in electricity production. Among thermochemical conversion, pyrolysis and gasification are of great importance in research, since these technologies are not yet widely applied. In combustion research, focus is given to pollutant formation, application of non-woody biomass, and implementation of combined heat and power production.

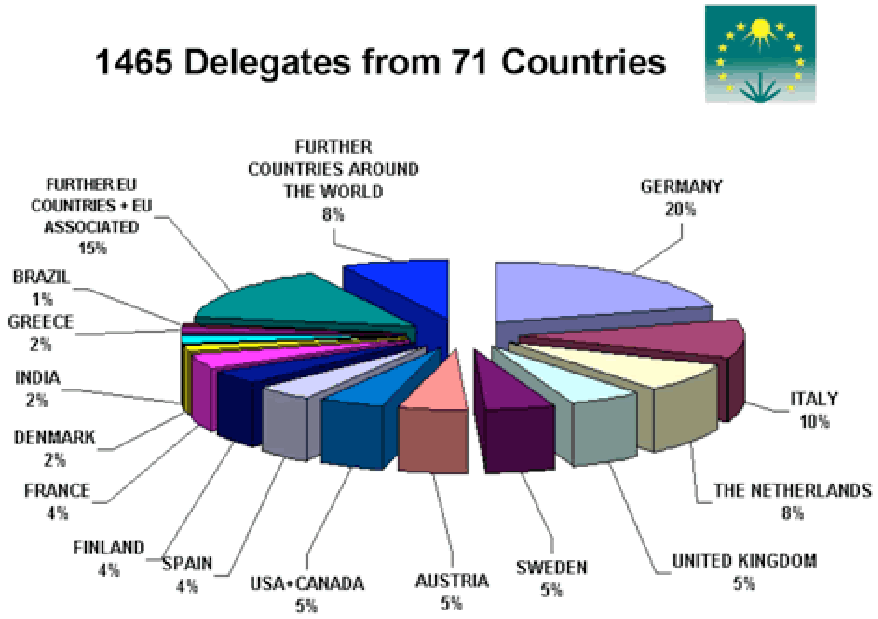

Figure 6.1 Distribution of participants in the 15th European Biomass Conference

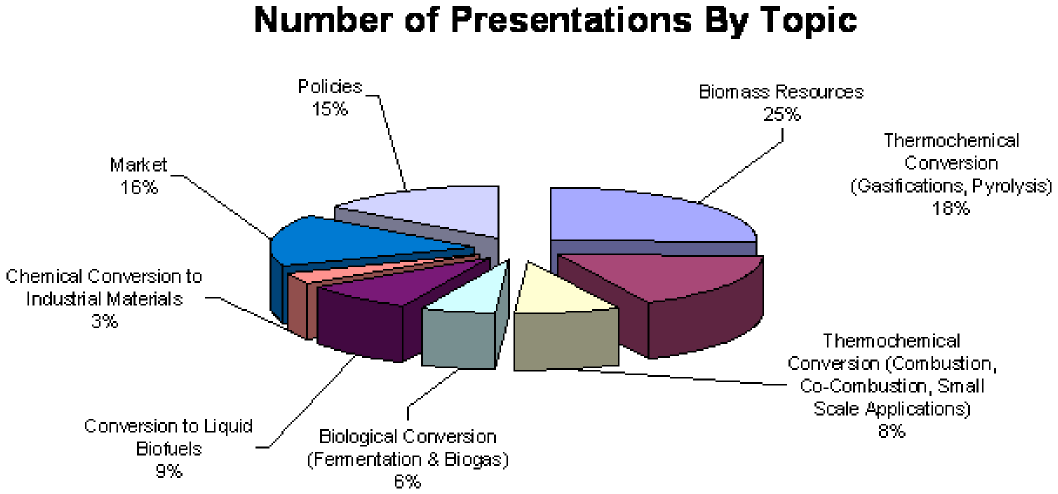

Figure 6.2 Distribution of topics in the 15th European Biomass Conference

6.2 Research topics

The main targets of research and development in biomass combustion are:

- Increase of efficiency:
  – Combustion efficiency
  – System efficiency for heat production
  – Electric efficiency for combined heat and power production (CHP) and for dedicated power production

- Reduction of airborne pollutants, especially:
  – Uncombusted pollutants by primary measures, both gases (CO and HC), as well as particulate matter
  – PM by secondary measures (both from uncombusted pollutants and from mineral matter)
  – NO_X by primary and secondary measures
  – Additional pollutants such as PCDD/F for contaminated biofuels

- Use of non-woody biomass such as straw, grass, agricultural residues

- Co-use of biomass with fossil fuels, especially co-firing biomass in coal fired power stations

- New applications of combined heat and power production with different targets:
  Smaller size, lower cost, higher efficiencies than steam cycles. For this purpose, organic Rankine cycles (ORC), Stirling engines, and indirectly fired gas turbines (hot air turbine) are being investigated.

6.3 Research institutions

Switzerland

Verenum
Contact: Thomas Nussbaumer
Langmauerstrasse 109, CH – 8006 Zürich
++41 (0)44 377 70 70
http://www.verenum.ch
Activities: Biomass combustion 10 kW – 10 MW, pollutant formation, primary and secondary measures for pollutant reduction, legislation, consultancy, quality assurance, plant optimisation

Hochschule Luzern – Technik & Architektur (University of Applied Sciences Lucerne)
Bioenergy and Sustainability Research Group
Technikumsstrasse 21, CH – 6048 Horw
Contact: Thomas Nussbaumer
http://www.hslu.ch
Activities: Biomass combustion 10 kW – 10 MW, pollutant formation, emission monitoring, primary and secondary measures for pollutant reduction, CFD modeling, development of improved combustion technologies

Ökozentrum Langenbruck (Centre of Appropriate Technology and Social Ecology)
Contact: Christian Gaegauf
Schwengiweg 12, 4438 Langenbruck/Schweiz
http://www.oekozentrum.ch
Activities: Biomass combustion 10 kW – 70 kW, emission monitoring

Germany

Technologie und Förderzentrum (TFZ)
Hans Hartmann
Schulgasse 18, 94315 Straubing
http://www.tfz.bayern.de/
Activities: Biomass combustion 10 kW – 70 kW, emission monitoring, logistics of agricultural biomass harvesting, testing of boilers and stoves

University of Stuttgart
Institute of Process Engineering and Power Plant Technology
Pfaffenwaldring 23, D-70569 Stuttgar
Günther Baumbach: Air Quality (residential wood combustion)
Activities: Emission monitoring of residentail wood combustion
Uwe Schnell: Combustion Technology (power plants)
Activities: CFD modeling of large utility boilers
http://www.ivd.uni-stuttgart.de/

Technical University Hamburg-Harburg
Eißendorfer Straße 40, D – 21073 Hamburg
Martin Kaltschmitt, Wolfgang Calmano, Joachim Gerth
http://www.tu-harburg.de/iue/
Activities: Techno-economic assessment and life cycle assessment of bioenergy, emission monitoring

Fachagentur nachwachsende Rohstoffe e.V.
http://www.fnr.de/
Activites: Coordination of German research studies concerning renewable resources (no own research)

Fraunhofer Wilhelm-Klauditz-Institut Holzforschung (WKI)
Bienroder Weg 54 E, D – 38108 Braunschweig
Prof. Dr. Rainer Marutzky
www.wki.fraunhofer.de
Activities: Emission monitoring (mainly in the 80s and 90s, now focus on wood technology and indoor air quality)

Austria

In Austria, five research organizations, located in Vienna, Wieselburg, and Graz, are basically independent, but united in the „Austrian Bioenergy Centre (ABC)". ABC is a GmbH (limited liability company) and controlled by the share holders.
Due to the coordination by ABC, there is a theoretical apportionment of the tasks for the involved institutes. However, two of the five institutions in ABC (Uni Graz and Bios GmbH Graz) are controlled by one person (Ingwald Obernberger), who initially controlled more than 50% of the shares of ABC and controlled the activities of the total centre. This resulted in limited possibilities for cooperation with research institutes abroad due to strongly protected activities of ABC.

Austrian Bioenergy Centre				
BLT Wieselburg	Technical University Graz	Bios GmbH	Technical University Vienna	Joanneum Research Forschungsgesellschaft mbH

Austrian Bioenergy Centre
Inffeldgasse 21b (same address as Bios GmbH)
A-8010 Graz
http://www.abc-energy.at/

Bios GmbH
Inffeldgasse 21b – 8010 Graz
Ingwald Obernberger
http://bios-bioenergy.at/
Activites: Biomass combustion, plant planning

BLT - Biomass · Logistics · Technology Francisco Josephinum
A-3250 Wieselburg, Rottenhauser Straße 1
Manfred Wörgetter, Leopold Lasselsperger, Günther Friedl
http://blt.josephinum.at/index.php?id=239
Activites: Testing of boilers and stoves, small scale biomass combustion (< 300 kW)

Technical University Graz
Institute for resource efficient and sustainable systems
Inffeldgasse 21 a – 8010 Graz
Ingwald Obernberger
http://rns.tugraz.at/index.php?&lang=_en
Activites: Biomass combustion, CFD modeling

Joanneum Research Forschungsgesellschaft mbH
Institute of energy research
Steyrergasse 17-19 – 8010 Graz
Josef Spitzer, Reinhard Padinger
http://www.joanneum.at
Activites: Biomass combustion, boiler development, process control

Sweden

SP Technical Research Institute of Sweden
Energy Technology
Claes Tullin, Linda Johansson
http://www.sp.se/en/units/energy/sidor/default.aspx
Activites: Emission monitoring

UMEÅ University
Enrgy Technologa and Thermal Process Chemistry
Christoffer Boman
http://www.umu.se/umu/eng/research/index.html
Activites: Combustion modeling

Finnland

University of Kuopio
Department of Environmental Science
Jorma Jokiniemi, Aerosol technology, P.O.Box 1627, FIN-70211 Kuopio
http://www.uku.fi/laitokset/ifk
Activities: Particle formation and measurement

Finland
Pasi Vainikka
VTT-Energy, PO Box 1603, FIN-40101 Jyväskylä, Finland
Activities: Biomass combustion, modeling, small scale and large scale (also fluidized bed)
http://www.vtt.fi/

Denmark

Department of Atmospheric Environment, National Environmental Research Institute
Fredriksborgvej 399
DK-4000 Roskilde

Department of Chemistry, University of Copenhagen
Universitetsparken 5
DK-2100 Copenhagen

Force Technology
Anders Evald
Hjortekærsvej 99 DK-2800 Lyngby
Activites: Boiler development (large scale)

Norway

SINTEF NBL (Norwegian Fire Research Laboratory)
Energy Research AS Sem Sælands vei 11, NO 7465 Trondheim
http://www.sintef.no/content/page3 2274.aspx
Activites: Testing of boilers and stoves

NTNU (Norwegian University of Science and Technology)
Department of Energy and Process Engineering
Johan E. Hustad, Øyvind Skreiberg
http://www.ntnu.no
Activites: Combustion modeling

Netherlands

Procede Biomass BV
PO Box 328, NL – 7500 AH Enschede
Sjaak van Loo, Jaap Koppejan
http://www.procede.nl/
Activites: Combustion control, coordination of IEA Bioenergy Combustion task (current task leader of International Energy Agency Bioenergy Task 32 „Biomass Combustion an Co-firing)

7 Conclusions

7.1 State-of-the-art of biomass combustion in Europe

In many countries in Europe, biomass combustion is widely applied on small and medium scales. Small-scale applications are mainly for residential heating. For this purpose, manually operated stoves and boilers are commonly applied, while pellet combustion is available as an alternative with automatic feeding but does not allow the use of log wood available from forests.

For log wood boilers, the technical standard was significantly improved in the past 30 years thanks to the application of the two-stage combustion principle with primary and secondary air, which is injected with mechanical ventilation and followed by a hot combustion chamber. This allows improvements in efficiency and a reduction of pollutant emissions, such as CO, which is often used as an indicator for the carbon burnout, as well as VOC and PM, which originate from soot and organic condensables. This exhibits a serious environmental impact. However, to ensure good combustion conditions in practice, operation at low load needs to be strictly avoided. For this purpose, the application of a heat storage tank is needed and mandatory in Switzerland. The use of log wood boilers without heat storage tanks and/or with simple combustion technology can lead to excessive pollutant formation. Due to a relevant number of existing wood boilers, which do not fulfill these requirements, log wood boilers are a relevant source of PM in the ambient air in some countries in Europe, which can be reduced by improved technology. For typical applications of log wood boilers in the United States (e.g. “outdoor wood boilers”), potential improvement is expected, since these boilers exhibit a fairly poor combustion technology, and they are typically operated without a heat storage tank, which is essential for simple wood boilers.

For wood stoves, minor improvements were achieved in Europe, since conventional combustion principles without fans are usually applied. Here, ideal operation is essential to avoid high-pollutant emissions in practice, such as ignition of the wood from the top instead of ignition from the bottom and use of small batches of small dry logs. As for boilers, throttling the combustion air to achieve operation at low load needs to be strictly avoided. Since the ideal type of operation is related to frequent adding of small logs, wood stoves are often operated non-ideally and also a relevant source of PM in the ambient air. Consequently, investigations of PM in the ambient air in alpine valleys during the winter season revealed that approximately 80% of the soot is originating from wood combustion.

To reduce PM emissions from residential wood combustion, small-scale electrostatic precipitators are under development and in the market implementation phase. However, the reduction potential is often relatively poor (less than 80% and often less than 50%) and is uncertain in practice. PM from residential wood combustion remains an important issue for the future and primary measures are of high priority, while precipitation is regarded as an additional measure.

As an alternative to manual operated devices, pellet boilers and stoves are available. Thanks to automatic feeding and small fuel size, improved combustion conditions with lower PM emissions can be achieved. Pellet combustion instead of manual stoves or badly operated boilers allows a reduction of PM emissions. The technology of pellet stoves and boilers in Europe is on a high technical level with usually very low emissions under stationary operation. However, boilers and stoves in practice are often operated with high excess air, leading to avoidable heat losses. In addition, automatic ignition and/or part load operation for glow bed maintenance can lead to periods of increased emissions. There is a potential of improvement, which is, however, of lower priority than the improvements needed to reduce PM from manual stoves and boilers.

For medium scale applications from 100 kW to 10 MW, automatic boilers for wood chips are available and widely applied. Thanks to high combustion temperature, such plants exhibit usually low emissions of uncombusted gaseous and solid carbon emitted as PM but exhibit relevant emissions of inhalable particles resulting from ash constituents in the fuel. For plants greater than 500 kW or a few MW depending on national emission limits, particle removal mostly by ESP and in some cases with fabric filters is applied. However, boilers for heating purposes are often operated at part-load or with periodic on/off operation. During such operation modes, the particle removal is often ineffective due to reduced flue gas temperatures. Therefore system integration, boiler management, and combustion control need to be improved in the future. In addition, there is an increasing need for particle removal for applications smaller than 1 MW, which need to be developed in the next years due to emission limit values resuming fine particle removal even for applications smaller than 1 MW, and in Switzerland from 500 kW. Finally, there is an interest in smaller particle removal equipment, especially for retrofitting existing plants that have limited space.

7.2 Relevance of PM emissions

Data on emission factors of residential wood combustion have been collected from 16 institutions in seven IEA countries. Wide 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 wide ranges from less than 20 mg/MJ (0.046 lb/MMBTU) under ideal conditions, to more than 5 000 mg/MJ (11.6 lb/MMBTU) under poor conditions (data refer to end energy indicated as lower heating value). Even national emission factors vary from less than 100 mg/MJ (0.23 lb/MMBTU) (measured as solid particles in the chimney) to almost 2 000 mg/MJ (4.6 lb/MMBTU) (measured in a dilution tunnel).

- For wood stoves, wide ranges are found due to different operation conditions. Consequently, high priority should be given to avoiding inappropriate operation of manual wood combustion appliances. Excessive PM emissions are found during smoldering conditions at reduced load and throttled air supply. This type of operation needs to be strictly avoided but nevertheless seems to be relevant in practical operation in many countries.

- For wood boilers, excessive PM emissions are reported for boilers operated without heat storage tank. This is in line with the observation found for stoves, since boiler operation for house heating without heat storage tanks often leads to part load combustion. In Switzerland, heat storage tanks for log wood boilers are virtually mandatory (i.e., an operation without heat storage tank is not permitted except if the boiler fulfills the emission limits at 30% load, which is not achievable with nowadays technology).

- For residential wood boilers, the type of combustion also significantly influences the PM emission. Modern boilers with forced downdraft combustion and electronic combustion control devices allow 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 approx. 30 mg/MJ (0.07 lb/MMBTU) are reported with a relatively narrow variation from < 20 to < 60 mg/MJ (< 0.046 to < 0.07 lb/MMBTU). 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 is scarce and 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 particle re–moval will result in higher emissions (i.e. an expected increase of a factor of 3 to 5 in PM and NO_X for agricultural pellets instead of wood pellets). Domestic scale applications should be restricted for good quality wood pellets, while other pellets should be reserved for applications in larger plants which are equipped with flue gas cleaning.
- For automatic combustion plants, the emission factors without electrostatic precipitator (ESP) or fabric filter (FF) are relatively high, typically between 50 to 100 mg/MJ (0.115 to 0.23 lb/MMBTU), which, under good combustion conditions, is attributed to high emissions of inorganic particles. 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 made stricter. The situation of typical PM emissions will change in many countries in the near future, since particle removal allows clean gas emissions of less than 30 mg/MJ (0.07 lb/MMBTU) (simple ESP) or less than 10 mg/MJ (0.023 lb/MMBTU) (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 (at 160° acc. to VDI or at 120°C acc. to EPA), solid particles plus condensables (SPC) found by liquid quenching at < 20° or < 5°C, 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 and sampling in the chimney reveals significantly higher concentrations in the diluted flue gas and shows that the condensable matter is found partially or quantitatively as filterable material after a moderate dilution at a dilution ratio in the order of 10 of the flue gas with cold air. This results in a fast temperature reduction at a moderate decrease of the partial pressure of volatile organic compounds. Consequently, PM emission 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 PM measurements in the ambient air, where a higher contribution from wood combustion is found than expected from emission factors used currently in Switzerland [Prévot et al. 2006]. On the other hand, evaporation of volatiles may occur during further dilution to a dilution ratio of 10 000 in the

ambient air. This can happen because of a significant reduction of the partial pressure of volatile organic compounds. The primary aerosols expected in the ambient air might be over estimated by measurements in the dilution tunnel. However, for the final PM concentration in the ambient air, the formation of secondary aerosols needs to be considered, leading to an additional increase of total PM resulting from wood combustion. This is induced by photochemical oxidation to secondary organic aerosols (SOA).

- Due to different samplings of PM, a comparison of data reported from countries with regulations on solid particles, such as Germany, Austria, and Switzerland, cannot be directly compared with data reported from countries such as Norway using dilution tunnels. 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. For measurements according to US EPA, sampling in the stack or in the dilution tunnel can be applied, which may also result in different emission factors and which also needs to be considered for comparison with European emission factors.
- Condensables from wood combustion have been identified as highly toxic substances that can significantly contribute to total PM in the ambient air. For improving emission inventories to calculate ambient air quality levels, it is essential to consider solid particles and condensables found in the stack. Furthermore, the potential formation of secondary organic aerosols resulting from volatile organic compounds, which are not trapped in the condensables, need to be considered as well. Since organic condensables are highly toxic, while solid particle can exhibit low toxicity (in case of salts) or high toxicity (if resulting from incomplete combustion or from contaminants such as heavy metals), a separate measurement of both parameters is advantageous. However, measurement of solid particles only requires less equipment, s less time consuming and still gives a performance value for PM emissions for comparison of different combustion appliances. In the case of nearly complete combustion, as found in modern automatic wood boilers under good operating conditions, the concentration of condensables is usually insignificant.
- A survey of equipment used for particle size measurement reveals that cascade impactors are used in almost all laboratories dealing with particle measurement. In addition, half of the participating institutions use scanning mobility particle sizers (SMPS) and/or electric low-pressure impactors (ELPI). Optical particle counters (OPC), aerodynamic particle sizers (APS), and tapered element oscillating micro-balances (TEOM) are currently used.

8 References

Dockery D., C. Pope, X. Xu, J. Spengler, J. Ware, M. Fay, B. Ferris, F. Speizer. (1993): An association between air pollution and mortality in six U.S. Cities. *The New England J. of Medicine*, Vol. 329, pp. 1753-1759.

Donaldson K., Brown D., Clouter A., Duffin R., MacNee W., Renwick L., Tran L., Stone V. (2002): The pulmonary toxicology of ultrafine particles. *Journal of Aerosol Medicine,* 15(2), pp. 213-20

EPA, access to site: 07/10/2007, http://www.epa.gov/air/oaqps/efactors.html

EPA: National Ambient Air Quality Standards (NAAQS), 2007, 6/20/2007, http://www.epa.gov/air/criteria.html

Hausammann, B.: Beurteilung der Vergleichbarkeit verschiedener Messverfahren zur Bestimmung der Partikelgrössenverteilung von Feinstäuben aus Verbrennungsprozessen, Diplomarbeit ETH Zürich am Departement UMNW bei T. Nussbaumer und U. Lohmann, Zürich 2006

Johansson, L.; Leckner, B.; Gustavsson, L.; Cooper, D.; Tullin, C.; Potter, A.: Emission characteristics of modern and old-type residential boilers fired with wood logs and wood pellets, Atmospheric Environment, Vol 38, Issue 25, 2004, 4183–4195

Jokiniemi, J.: Aerosol sampling and measurement techniques with a special focus on small-scale biomass combustion systems, 3rd International Workshop on Aerosols from Biomass Combustion, International Energy Agency (IEA) Bioenergy Task 32, Jyväskylä (Finland), 3 September 2007, www.ieabcc.nl

Kaufmann, H.; Nussbaumer, T.; Baxter, L.; Yang, N.: Deposit formation on a single cylinder during combustion of herbaceous biomass. Fuel 2000, 79, 141-151

Kessler F., Knechtle, N., Frischknecht R.: Umwelt Schrift Nr. 315, BUWAL (Swiss Federal Office of Environment), Berne 2000

Klippel, N.; Nussbaumer, T.: Health relevance of particles from wood combustion in comparison to Diesel soot, 15th European Biomass Conference, International Conference Centre, Berlin 7–11 May 2007 (a)

Klippel, N.; Nussbaumer, T.: Einfluss der Betriebsweise auf die Partikelemissionen von Holzöfen, Bundesamt für Energie und Bundesamt für Umwelt, Schlussbericht, Zürich 2007, ISBN 3-908705-12-6, 2007 (b)

Lipsky, E.; Robinson, A.: Effects of Dilution on Fine Particle Mass and Partitioning of Semivolatile Organics in Diesel Exhaust and Wood Smoke, Environ. Sci. Technol. 2006, 40, 155–162

McMurry, P.; Shepherd, M.; Vickery, J. (eds.): Particulate Matter Science for Policy Makers, A NARSTO Assessment, Cambridge press, 2004, ISBN-13: 9780521842877, ISBN-10: 0521842875, also available as pdf from www.narsto.org

Morf, Ph.; Hasler, Ph., and Nussbaumer, Th.: Mechanisms and kinetics of homogeneous secondary re¬actions of tar from continuous pyrolysis of wood chips, Fuel, (81) 2002, 843–853

NARSTO 2005: Improving Emission Inventories for Effective Air Quality Management Across North America, A NARSTO Assessment, NARSTO 05-001, www.narsto.org

NESCAUM and MJB Associates: Assessment of carbonaceous $PM_{2.5}$ for New York and the region, Final Report 08-01, March 2008

Nordic Council of Ministers, Sternhufvud C., Karvosenoja N., Illerup J., Kindbom K., Lükewille A., Johannson M., Jensen D., Particulate matter emissions and abatement options in residential wood burning in the Nordic Countries, Copenhagen 2004; p. 34

Norwegian standard NS 3058-2 June 1994, Enclosed wood heaters Smoke emission, Part 2: Determination of particulate emission

Nussbaumer, T.: Combustion and Co-combustion of Biomass: Fundamentals, Technologies, and Primary Measures for Emission Reduction, Energy & Fuels, Vol. 17, No 6, 2003, 1510–1521

Nussbaumer, T.: Overview on particles from biomass combustion, 14th European Biomass Conference, Paris, 17-21 October 2005

Nussbaumer, T.; Czasch, C.; Klippel, N.; Johansson, L.; Tullin, C.: Particulate Emissions from Biomass Combustion in IEA Countries: Survey on Measurements and Emission Factors, International Energy Agency (IEA) Bioenergy Task 32 and Swiss Federal Office of Energy (SFOE), Zürich 2008, ISBN 3-908705-18-5, www.ieabcc.nl, www.verenum.ch

Oser, M.; Nussbaumer, Th.: Low particle furnace for wood pellets based on advanced staged combustion, Science in Thermal and Chemical Biomass Conversion, Volume 1, CPL Press, Newbury Berks (UK), 2006, ISBN 1-872691-97-8, 215–227

Pagels, J.; Johansson, L.; Hagström, M.; Szpila, A.; Bohgard, M.; Tullin, C.; Sanati, M.: Intercomparison of SMPS, ELPI and APS 3320 during sampling of particles emitted from a domestic wood pellet burner, 6th international Aerosol Conference, September 8-13, 2002, Taipei, Taiwan

Prévôt, A.; Wehrli, M.; Alfarra, M.; Lanz, V.; Szidat, S.; Hueglin, C.; Gehrig, R.; Sandradewi, J.; Weimer, S.; Baltensperger, U.: The high PM10 episode in January/ February 2006, *10. International ETH-Conference on Combustion Generated Nanoparticles*, Zürich, 21 - 23 August 2006

Robinson, A.: Semivolatile Emissions and Photochemical Aging: Implications for Human Exposure and Control Strategies, Environmental Monitoring, Evaluation, and Protection in New York: Linking Science and Policy (EMEP), Conference by New York State Energy Research and Development Authority (NYSERDA), Albany, NY, USA, November 15-16, 2007, www.nyserda.org

Robinson, A.; Donahue, N.; Shrivastava, M.; Weitkamp, E.; Sage, A.; Grieshop, A.; Lane, T.; Pierce, J.; Pandis, S.: Rethinking Organic Aerosols: Semivolatile Emissions and Photochemical Aging, SCIENCE, Vol 315, 2 march 2007, 1259–1262

Ryde, D. & Johansson, L., *Partikelmätning vid vedeldning -Jämförelse mellan provtagning i skorsten och spädtunnel*, Slutrapport för Energimyndighetsprojekt nr 30207-1, SP Arbetsrapport 2007:15, Juli 2007, Borås (In Swedish, summary in English)

Shrivastava, M.; Lipsky, E.; Stanier, C.; Robinson, A.: Modeling Semivolatile Organic Aerosol Mass Emissions from Combustion Systems, Environ. Sci. & Technol., published on Web 03/09/2006

UBA: *Hintergrundpapier zum Thema Staub/Feinstaub (PM),* Umweltbundesamt Berlin, 2005; p.3

Vock, W.; Jenni, A.: *Bericht zur 1. und 2. Mess-Serie: Emissionsarme Anfeuermethoden für Stückholzfeuerungen*, Bundesamt für Energie, Bundesamt für Umwelt, Kantone AG, BE, BL/BS, LU, SH, SG, SO, TG, TI, VD, ZH, Maschwanden, Juli 2007

World Health Organization (WHO): Airquality Guidelines for particulate matter, ozone, nitrogen, dioxide and sulphur dioxide, Global Update 2005,; 2006

World Health Organization (WHO): Health Aspects of Air Pollution, Results from the WHO Project „Systematic Review of Health Aspects of Air Pollution in Europe), 2004; p 10

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