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# A Review on Particle Emissions from Small Scale Biomass Combustion

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**Abstract-** Combustion of biomass as fuels in small scale heating appliances is a common source of particle emissions. Majority of the particles is less than 1 μm (micrometer) and emitted directly to the atmosphere from the combustion devices. There is a growing concern worldwide about particle emissions from biomass combustion. Types of particles, formation mechanisms, their characteristics and available measurement techniques are discussed in this paper. Particle emission characteristics on small scale biomass combustion have also been discussed. The review findings have been summarized into three categories to show how combustion appliances and fuel affect the mass concentrations, number concentrations, corresponding size distributions and chemical compositions. Mass concentrations of particles in the flue gas from small scale combustion appliances reported in the literature to be in the range of 7-67 mg/Nm3, while particle number concentrations in the range of 0.8 x 107- 5.5 x 109 particles/cm3. The dominating chemical compositions of the particle emissions in the fine mode were potassium fraction followed by sulphur, chlorine and sodium and consequently dominating chemical compounds were $K_2SO_4$ (potassium sulphate) and KCl (potassium chloride). From the literature it is clear that particle emissions from biomass combustion are closely related not only to the fuel properties but also to the combustion conditions and combustion appliances.

**Keywords-** Particle formation, measurement techniques, mass/number concentrations, size distributions

## 1. Introduction

Combustion of biomass is the oldest and still today the worldwide most spread out energy source used in a variety of applications for production of heat and power as well as for cooking. World energy supplies have been dominated by fossil fuels mix for decades, approximately 80% of the total use [1-3]. Today biomass contributes about 13% of the world energy demand [2]. Biomass contributes in the industrialized countries roughly 12% to the total energy supplies, but in developing countries this is about 35% of the energy demand [2, 4]. Contribution of biomass is even over 50 to 90% of the total energy demand in quite a number of these countries [5]. There is a growing interest using of biomass fuels for energy production purposes across the world. The utilization of biomass within the European Union (EU) has strongly increased over the last decades, and the ambitions of the EU for the use of biomass are high [2]. The European Union has set a target to produce at least 20% of energy from renewable sources by 2020 [6, 7]. Belgium government has also set a target to share 17% of energy from renewable energy sources by 2020 [6-9]. Biomass is the broadcast field in renewable energy. Biomass is seen as one of the options to mitigate greenhouse gas emissions and substitute fossil fuels [8-10].

Small scale combustion appliances are mainly used for the purpose of residential heating. Different types small scale combustion appliances such as wood stove, pellet burner, pellet boiler, wood log boiler, wood chip boiler are commonly used nowadays [11-14] in Europe as well as in Belgium. Different forms of biomass fuels such as wood logs, wood chips, wood pellets, saw dust, forest residues, straw etc. are used as fuel in these appliances [11-14]. Several studies show that combustion of biomass as fuels in small scale heating appliances is a common source of both particulate matter (PM) and gaseous emissions such as fine particles, polycyclic aromatic hydrocarbons (PAH), volatile organic compounds (VOC) and carbon monoxide, carbon dioxide, nitrogen oxide, sulphur oxide [10-12, 15-26]. In comparison to liquid and gaseous fuels, the emissions of particulate matter from biomass fuel are high [6, 8, 10, 23, 24]. There is a growing concern worldwide about particle emissions from biomass combustion. Majority of the particles is less than 1 μm (micrometer) and emitted directly to the ambient air from the combustion devices [16, 17]. A number of studies have shown that increased particle concentrations in the ambient air correlate with adverse health effects in the exposed population, including respiratory and cardiovascular illnesses as well as increased mortality [10, 17-26]. Further, it has been reported in the literature that in the case of combustion related particles, the fine particle fraction is especially harmful to human health [6-10, 17-27].

Another concern of particle emissions from biomass combustion is the influence on the performance of boiler operation. A fraction of these particles deposits on boiler surfaces, causing operational problems such as corrosion, fouling and as a result reduced combustion efficiency [6, 8-13, 18-24, 27, 28]. Besides, fine particle emissions from combustion sources are important cooling agents in the atmosphere. Cooling occurs directly by absorbing and scattering the incoming solar radiation as well as indirectly through acting as cloud condensation nuclei that form clouds by growing into cloud droplets. Clouds then reflect the radiation away from the atmosphere [6, 12, 20]. These effects are also strongly dependent on the chemical properties of particles.

There is scarce review paper on particle emissions from small scale biomass combustion in the literature concerning mass concentrations, number concentrations, size distributions and chemical composition. Some review [20] discussed on particle mass concentration only and not focused all these issues together in a paper. There is a need such kind of review paper providing detailed information on particle emissions from commonly used small scale biomass combustion appliances. The objectives of this paper is to review available data on particle emissions from small scale biomass combustion and measurement techniques applied in characterizing particle emissions in terms of mass concentrations, number concentrations, size distributions and chemical compositions.

This review paper is presented as follows. Firstly, an overview of types of particles and their formation mechanisms from biomass combustion are discussed in Section 2. Then, particle emissions characteristics, available measurement techniques and their comparison are presented in Sections 3 to 4. After that, particle emissions data available in the literature from different small scale biomass combustion appliances is briefly discussed in Section 5 in order to provide in depth knowledge as assistance to readers interested in this research field. Section 6 summarizes the literature data into three categories to show how combustion appliances and fuel affect the mass concentration, number concentration, size distributions and chemical compositions. Finally, Section 7 draws the conclusion of this paper.

## 2. Particle Formation from Biomass Combustion

Particle formation from biomass combustion depends on various factors such as combustion conditions, fuel properties, combustion appliances, excess air, and boiler loads etc. [6, 19, 22, 28].

### *2.1. Classifications/types of particles*

Various classifications are used to define particle sizes. Particles smaller than 1 μm (micro meter) in diameter are often called fine particles, the so called combustion aerosols [6, 22]. Combustion aerosol is a dynamic mixture of gases, vapours and particles in a flue gas. These fine particles are generally formed from elements that are vaporized during combustion, which later saturate and form fine particles by nucleation. The nucleated particles grow further by coagulation, agglomeration, condensation and surface reaction. Particles larger than 1 μm in diameter are called coarse particles contain mainly from char or ash species with low vapour pressures which do not vaporized during combustion [10, 22, 34]. The following definitions are used in this paper: PM10, PM2.5, and PM1 refer generically to particles with an aerodynamic diameter smaller than 10, 2.5 and 1 μm respectively [6, 12, 22]. These particle classes are always related to the aerodynamic diameter which represents the diameter of a spherical particle with a density of 1000 kg/m3 having the same in air as the particle of interest [6, 22].

Combustion particles from biomass fuel can be divided into two categories such as primary and secondary particles. Primary particles form at high temperatures in the combustion zone and secondary particles form in the flue gas plume or in the atmosphere. This paper mainly focuses on primary particles formed in the combustion zone. There are mainly three sources of primary particles according to origin and formation mechanism and these particles are emitted directly to the ambient air from the combustion devices [6, 22, 28-31]. Formation of these particles varies with combustion conditions for different fuels in different appliances.

- Soot particles
- Organic particles
- Ash particles

Soot and organic particles originate from combustible material, formed due to incomplete combustion, while ash particles are non combustible material introduced into the furnace. The following Sections 2.2 to 2.4 briefly present the formation mechanisms of different types of primary particles.

### *2.2. Formation of soot particles*

Soot is a complex mixture consisting mainly of amorphous elemental carbon (EC) and organic material. Soot particles are formed mainly inside the flame in the fuel rich area via complex mechanisms. There is a limited literature available concerning soot particle formation from biomass combustion.

Soot formation starts during devolatilization and combustion of volatiles when hydrocarbon fragments leave from the fuel particles. These fragments then crack into smaller pieces and react with one another and surrounding gases to form aromatic rings. These aromatic rings then start to form polycyclic aromatic hydrocarbon (PAH). Further growth of PAH leads to form soot [6, 12, 23, 30-32]. Generally, two pathways for the formation of soot nuclei can be mentioned. Firstly, at lower temperatures aromatic hydrocarbons produce soot directly by growing into graphite-like structure. Secondly, at higher temperatures both aliphatic and aromatic hydrocarbons first fragment, which is followed by polymerization of the fragments to larger molecules, forming soot. Thereafter, the particles grow larger by surface reactions, coagulation and agglomeration [6, 31, 32]. The resulting soot particles are thus composed of smaller spherical particles as shown in Figure 1 [23, 30, 32]. The formation process depends mainly on the fuel, combustion condition and flame type. In industrial scale biomass combustion units, the amounts of soot in the emissions are typically negligible, while in traditional small scale combustion units, soot is an important fraction in fine particle emissions [6, 33].

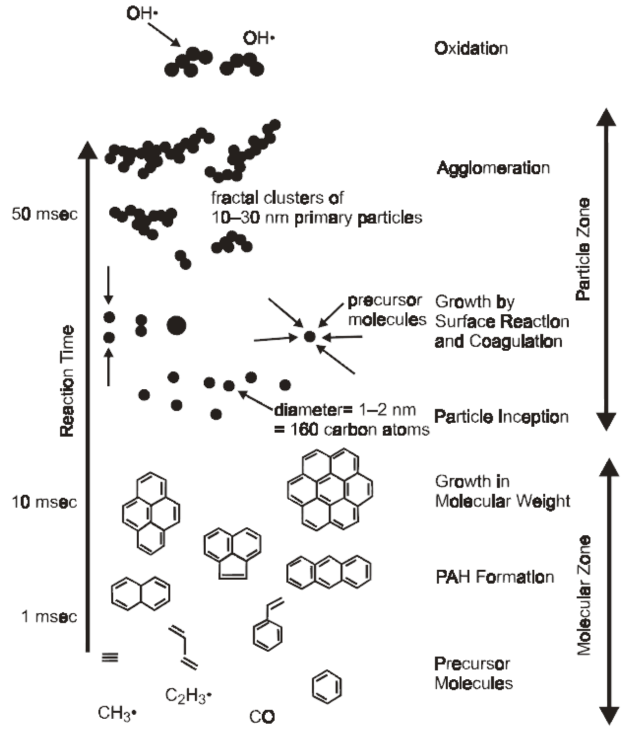

**Fig. 1.** Schematic picture of soot formation [23, 30, 32]

### *2.3. Formation of organic particles*

When biomass is heated, it decomposes forming a large variety of different organic compounds with highly different vapour pressures and molecular structures. Organic particles can remain in the flue gas formed due to incomplete combustion. The main part of the organic material found in fine particles is usually condensed at far below the temperature of 500 °C [33, 34]. Depending on environmental conditions, organic particles can be present in liquid or gaseous form. If the combustion is highly incomplete, heavy complex organic compounds are released to the flue gas. Poor combustion conditions can also be associated with natural fires that are a large source of organic matter in the atmosphere [29]. They are typically divided according to their boiling points into very volatile organic compound (VVOC), volatile (VOC) and semi volatile organic carbon (SVOC) compounds. Incomplete biomass combustion produces hundreds of different organic compounds [19, 29]. One of the most important VOC from biomass combustion is methane, which is also a very strong greenhouse gas. In flue gas conditions, the organic vapours condense mainly on existing fine particles through condensation and/or adsorption [33].

### *2.4. Formation of ash particles*

Solid fuels such as biomass contain considerable amounts of ash forming inorganic elements [35]. In the combustion process, these inorganic species produce a combustion product called ash. The behaviour of ash forming species is significantly influenced by the fuel ash properties, i.e. ash composition, the chemical form and binding of the ash forming materials. In addition, ash behaviour varies largely between different combustion technologies and combustion conditions. Ash forming species in biomass fuels can be divided into three categories [6, 22, 30, 35], such as: (i) non volatile elements like calcium (Ca), silicon (Si), magnesium (Mg), ferrous (Fe), aluminum (Al), etc., (ii) easily volatile elements like potassium (K), sodium (Na), sulfur (S), chlorine (Cl), etc., and (iii) easily volatile heavy metals like zinc (Zn), cadmium (Cd), lead (Pb), etc.

The major share of the ashes formed during biomass combustion leaves in the furnace called bottom ash. This fraction mainly consists of non volatile species but also contains the not released part of the easily volatile elements. Moreover, a minor portion of the ash particles is entrained from the fuel bed with the flue gas and forms the coarse fly ashes (>1 μm). These coarse fly ash emissions are in a particle size range between some μm to about 200 μm [29, 30]. The fine ash particles (<1 μm) are formed from the easily volatile inorganic elements, released from the fuel to the gas phase during combustion. Potassium, sulphur and chlorine are the most relevant element during the combustion of biomass fuels whereas sodium and heavy metals (zinc and lead) provide minor contributions. In the gas phase, these species undergo reactions resulting in the formation of alkaline (K, Na) metal chlorides, sulphates, carbonates, and heave metals oxides [6, 22, 30, 35]. These fine ash particles are formed by nucleation, condensation, surface reactions, coagulation and agglomerations.

Inorganic elements such as K, Cl and S from annual biomass release above 700 °C, below 500 °C and 500 °C respectively [36]. H Wiinikka [37] observed that the formation of combustion generated particles released from three different mechanisms: (i) coarse particles were formed from residual fly ash particles, (ii) fine fly ash particles were produced from the vaporization, condensation, nucleation of easily volatilized ash components and (iii) fine organic particles, soot were produced from incomplete combustion.

The particle formation pathways during biomass wood combustion under fixed bed conditions are shown in Figure 2 [6, 34]. Part of the inorganic elements contained in the fuel may be released and form inorganic gas species and particulate. It can be seen, from the Figure 2 that the particulate matter can be formed by different pathways, which lead to a characteristic bimodal particle size distribution. One is the fine mode (< 1 μm), in which the main route of particle formation is nucleation and condensation from the gas phase. The other is the coarse mode (>1 μm), which mainly consists of non-volatilized ash residuals and results in fly ash particles. The fine particles are mainly formed of potassium salts such as $K_2SO_4$ (potassium sulphate), KCl (potassium chloride), $K_2CO_3$ (potassium carbonate) and smaller amounts of zinc, sodium and organic material.

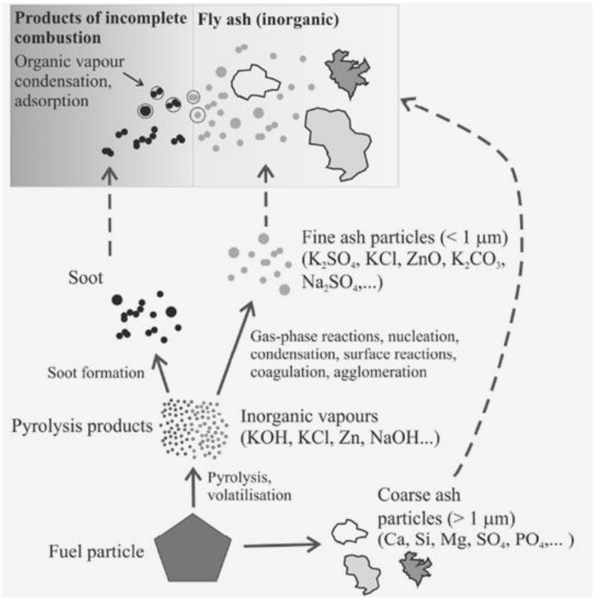

**Fig. 2.** Particle formation pathways from biomass wood combustion [6, 34]

## 3. Particle Emission Characteristics

The particle emissions characteristics are generally discussed in literature in terms of the following parameters [21, 23, 24].

- Mass concentration and mass size distribution
- Number concentration and number size distribution
- Chemical composition

The first two characteristics are called the physical properties of the particles and the last one is called the chemical properties. Mass concentration is defined as the mass of particles per unit volume of flue gas, while mass size distribution is mass concentration distributed over particle size. Number concentration of particles is number of particles per unit volume of flue gas, and number size distribution is number concentration distributed over particle size. The units expressed in this paper for mass concentration and number concentration are mg/Nm3 and particles/cm3 respectively. Chemical characteristics relate mainly to chemical constituents include elements, organic compounds of particulate matter.

## 4. Particle Measurement Techniques

The measurement of particles from biomass combustion appliances is very challenging. The particle size range is very large, and the flue gas contains particles that vary from few nanometers (nm) to micrometers (μm) in size.

### 4.1. *Mass concentration, number concentration and size distributions*

Measurements of particles are conducted in terms of mass concentrations, number concentrations and their size distributions. There are several measurement techniques (instruments) available for online measurements of particle characteristics. The selection of the measuring instruments for particle emissions and their size distributions is important, since different instruments have specific advantages and disadvantages. The commonly used state of the art instruments on particle emissions for the mass and number concentrations and their size distributions are given below. A comparison among these instruments is presented in Table 1 [6, 20, 24, 38-40].

- Electrical Low Pressure Impactor Plus (ELPI+)
- Electrical Low Pressure Impactor (ELPI)
- Aerodynamic Particle Sizer Spectrometer (APSS)
- Scanning Mobility Particle Sizer (SMPS)
- First Mobility Particle Sizer (FMPS)
- Dekati Low Pressure Impactor (DLPI)
- Tapered Element Oscillating Micro Balance (TEOM)

T Nussbaumer [24] made a comparison of different instruments shown in Figure 3 for the simultaneously measurement of particle number concentration and number size distributions in the flue gas from a pellet burner. In Figure 3, Electrical Low Pressure Impactor (ELPI) and Scanning Mobility Particle Sizer (SMPS) show a reasonable agreement in the submicron range. In the super-micron range, measurements with ELPI lead to far higher values than Dekati Low Pressure Impactor (DLPI) and DLPI leads to far higher values than Aerodynamic Particle Sizer (APS).

### 4.2. *Chemical compositions*

Besides the characterization of particle emissions by their particle size distribution and concentration in the flue gas, also their chemical composition characterization is important to know for an overall evaluation. This analysis can provide information on combustion conditions and mirrors the ash content of the fuel. The chemical analysis can be done off-line in using sample collection from a filter or a cascade impactor. Chemical analysis of particle emissions can be conducted by the following instruments/methods:

- Energy Dispersive Spectroscopy (EDS)
- Energy Dispersive X-ray Spectroscopy (EDX)
- Environmental Scanning Electron Microscopy (ESEM)
- Inductively Coupled Plasma-Mass Spectrometry (ICP-MS)
- Inductively Coupled Plasma-Optical Emission Spectrometry (ICP-OES)
- Particle Induced X-ray Emissions (PIXE)
- Scanning Electron Microscopy (SEM)
- Transmission Electron Microscopy (TEM)
- Time of Flight-Secondary Ion Mass Spectrometry (TOF-SIMS)

**Table 1.** Comparison of different instruments for particle measurement [6, 20, 24, 38-40]

| 0 | ELPI+ | ELPI | APSS | SMPS | FMPS | DLPI | TEOM |
|---|---|---|---|---|---|---|---|
| Size range | 6 nm to 10 µm | 7 nm to 10 µm | 500 nm to 20 µm | 2.5 nm to 1 µm | 5.6 nm to 560 µm | 30 nm to 10µm | Depends on pre-cutting |
| No. of size classes | 14 | 12 | - | - | 16 | 12 | - |
| Sample flow rate (lpm) | 10 | 10 or 30 | 1 | 0.2 to 2 | 10 | 10 or 30 | Main: 3 Bypass: 14 |
| Collection Plate diameter (mm) | 25 | 25 | - | - | - | 25 | - |
| Pressure (mbar) | 40 | 100 | 400-1030 | 750-1050 | 700-1034 | 100 | - |
| Weight (kg) | 15 | 35 | 10 | 23.2 | 32 | 5 | 18 |
| Measures | AD | AD | AD | MD | MD | AD | |
| Parameters | NCND | NCND | NCND | NCSD | NCND | MSD | MC |
| Advantages | Robust indicates changing in process well and large size ranges | | larger particles | very smaller particles | | large size ranges | Agree well with filter samples |
| Disadvantages | Results may be affected due to wide channels plate | | Not suitable for smaller particles | Not suitable for larger particles | | Not suitable for smaller particles | Filters needs to be replaced if concentration is high |

lpm = liter per minute, nm = nanometer, mm = millimeter, kg = kilogram

ELPI+ = Electrical Low Pressure Impactor Plus

ELPI = Electrical Low Pressure Impactor

APSS = Aerodynamic Particle Sizer Spectrometer

SMPS = Scanning Mobility Particle Sizer

FMPS = First Mobility Particle Sizer

DLPI = Dekati Low Pressure Impactor

TEOM = Tapered Element Oscillating Micro Balance

AD = Aerodynamic diameter, MD = Mobility diameter

NCND = Number concentration and size distribution

MSD = Mass size distribution, MC = Mass concentration

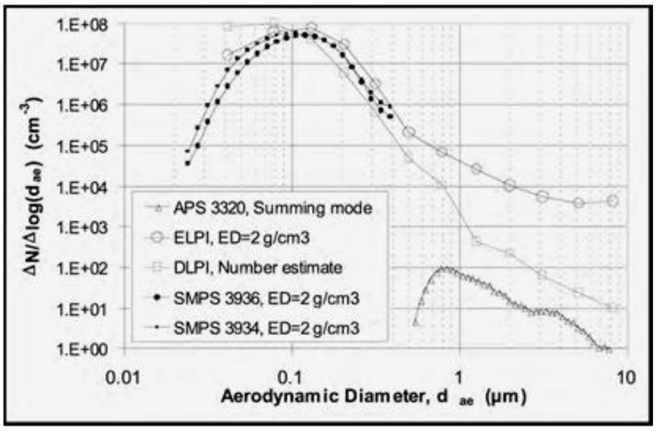

**Fig. 3.** Comparison of particle number concentration and number size distributions with different instruments at simultaneous measurement in the flue gas from a residential pellet burner [19], (ELPI = Electrical Low Pressure Impactor, APS = Aerodynamic Particle Sizer, SMPS = Scanning Mobility Particle Sizer, DLPI = Dekati Low Pressure Impactor)

## 5. Particle Emissions from Combustion

This section briefly reviews the findings/results published in the research articles available in the literature related to particle emissions from small scale biomass combustion during the period from 2000-2011. Several aspects associated with particle emissions from the researcher findings such as mass concentrations, number concentrations, size distributions and chemical compositions, measurement techniques/instruments are discussed below. All values related to emissions characteristics are presented in 13% oxygen concentrations.

*O Sippula* [6] investigated fine particle emissions from three small scale appliances such as a moving grate boiler (500 kW), a top feed pellet stove (8 kW) and a pellet boiler (20 kW). Stem wood pellets were fired all these appliances. ELPI was used to measure particle emissions characteristics after the dilution tunnel. From his results, it was observed that pellet stove gave highest emissions in terms of mass and number concentrations followed by moving grate boiler and pellet boiler.

*L S Johansson* [21] studied particle emissions from an old type wood log boiler, a modern wood boiler and a pellet boiler. Number concentrations and size distributions were measured by ELPI, while mass size distribution done by DLPI. She found that the mass concentration of particles was 180 times higher in old type wood boiler compared to the pellet boiler. She also observed that old type wood log boiler emitted larger number of particles than from wood pellet boiler. Therefore it is important to pay attention to the old type combustion appliances. It was seen from experiment that the variation in number size distribution was small with maximum around 130 nm (nanometer) from the flue gas of pellet combustion.

*I Obernberger* [22] investigated particle emissions from modern small scale combustion appliances such as a pellet boiler (20 kW), a wood chip boiler (40 kW) and a wood log boiler (30 kW). Mass concentration, particle size distribution and chemical composition of particle emissions were analyzed by BLPI, ELPI and Scanning Electron Microscopy (SEM)/Energy Dispersive X-ray Spectroscopy (EDX) respectively. The mean values of the PM10 emissions for the pellet boiler were found in the ranged between 13 to 18 mg/Nm3 at full load and 14 to 21 mg/Nm3 at partial load (50% of full load). For wood chip boiler investigated the respective values were between 28 to 56 mg/Nm$^3$ at full load and between 33 and 61 mg/Nm3 at partial load operation. For wood log boiler, the particle emissions were 8.8 mg/Nm3 at full load and 6.8 mg/Nm$^3$ at partial load. Modern wood log boiler has the lowest PM10 emissions compare to pellet boiler and wood chip boiler. This was mainly due to the fact that gasification of the fuel took place at rather low temperature. Particle mass and number size distributions for of all boilers were found peak in the size ranges of about 0.1 to 0.2 μm and with increasing concentration of particles in the flue gas. It was observed that particle size slightly increased due to enhanced coagulation effects and surface condensation. For all boilers, the dominating chemical compositions of the inorganic fraction of the particle emissions were K fraction followed by S, Cl and Na and consequently dominant compounds found in the fine mode were K2SO4 and KCl.

*L S Johansson* [32] investigated particle emissions from two domestic heating appliances such as a pellet stove and a pellet boiler, both having same capacity of 6 kW. The appliances were fired with wood pellets. Particle characterizations were done with an electrical low pressure impactor (ELPI) and a Dekati low pressure impactor (DLPI) and measurements were combined with EDX and time of flight-secondary ion mass spectrometry (TOF-SIMS) for particle chemical analysis. PM10 mass concentration was 34 mg/Nm3, PM10 number concentrations varied between 1.1 x 107 and 4.7 x 107 particles/Ncm$^3$ for pellet boiler. While PM10 mass concentration was 47 mg/Nm$^3$, PM10 number concentrations varied between 1.8 x 107 and 8.7 x 107 particles/Ncm$^3$, for pellet stove. It is observed from her investigation that pellet stove emitted higher mass and number concentrations compared to pellet boiler. Particle emissions were dominated by fine particles in both cases. The EDX analysis showed that the main inorganic components of the fine particles were potassium, sulphur, chlorine and smaller amount of sodium, magnesium and zinc were observed. The dominant compounds found in the fine mode were $K_2SO_4$ and KCl.

*C Boman* [33] studied inorganic particulate matter emissions from pelletized biomass fuels combusted in three different pellet burners (10-15 kW). The particle mass size distribution was determined by DLPI combined with Environmental Scanning Electron Microscopy (ESEM) for particle morphology and EDS for elemental composition. He observed that the emitted particles were mainly found in the fine (<1 μm) mode with aerodynamic diameters of 0.20-0.39 μm and an average PM1 of 89.5% ± 7.4% of total PM. The inorganic elemental compositions of the fine particles were dominated by potassium, chlorine, and sulfur, with minor amounts of sodium and zinc and the dominating alkali compound was KCl.

*Q Chen* [41] studied emission characteristics of small scale heating system for a 190 kW pellet boiler fired wood pellets with feeding rate of 13 kg/hr. Mass size distribution and total concentration of particulate matter were isokinetically measured by an eight stage Andersen impactor and the measurement was combined with inductively couple plasma-optical emission spectrometry (ICP-OES) for the analysis of particle chemical composition. The mass concentration of PM10 in the flue gas was 33 mg/Nm3 and the elemental analysis showed that the dominating chemical compositions of the inorganic fraction of the particle emissions were K fraction followed by S, Ca and Na.

*J Tissari* [42] studied fine particle emission from normal and smouldering combustion in a conventional masonry heater fired wood logs with different batches and sizes. After dilution tunnel, ELPI and SMPS were used to measure particle number emissions and size distributions, while DLPI used for mass size distributions. Elemental analysis of the fine particle emissions was performed by Scanning Electron Microscopy (SEM) and Energy Dispersive Spectroscopy (DES). He found that fine particle emissions from smouldering combustion conditions were six fold to that of normal combustion condition. But the particle number emissions from smouldering combustion were less than half of that from normal combustion. According to SEM and EDS analyses, he observed fine ash particles seemed to occur mainly as separate spherical or irregularly shaped particles but not as agglomerates. Fine ash particles were composed mainly of potassium, sulphur and zinc but also a lesser content of calcium, chlorine and sodium.

*C Gaegauf* [43] investigated particle emissions from various small scale biomass combustion systems including a wood log boiler (25 kW), a wood pellet boiler (17 kW) and a wood chip boiler (70 kW) with mechanical feed. The fuels were comprised of wood logs, wood pellets and wood chips respectively. SMPS was used to determine particle mass concentration and number concentration in the stack. The PM10 emissions were 42±17 mg/Nm$^3$, 29±0.5 mg/Nm$^3$, 67±8 mg/Nm$^3$ for wood log boiler, wood pellet boiler and wood chip boiler respectively. He observed that major part of the particle emissions up to 95% are fine particle in the range of between 30 and 300 nm. He also investigated the effect of excess air on the particle number concentration for wood chip boiler.

*M A Bari* [44] investigated particle emissions from a pellet stove (5 kW) and a wood log boiler (20 kW) under two combustion conditions i.e. complete combustion with relatively good combustion having CO concentration <300 mg/Nm3 over the whole burnout and incomplete combustion with lack of air characterized by CO concentrations >5000 mg/Nm3 over the whole burnout, referred to 13% oxygen. The measurements were done from the stack using BLPI and SMPS for mass concentration and number size distribution. The particle mass (PM10) concentrations for pellet stove were 201 mg/Nm$^3$ and 31 mg/Nm3 for complete and incomplete combustion respectively, while 98 mg/Nm$^3$ and 48 mg/Nm$^3$ for wood log boiler. PM1 number concentrations varied between 1.5-5.4 x 107 particles/Ncm$^3$ for pellet stove, while 1.2-4.7 x 107 particles/Ncm$^3$ for wood log boiler for complete combustion. He observed that emission concentrations from these appliances were higher during incomplete combustion compared to complete combustion and size distribution of emitted particles was unimodal in the size range of 0.06 to 0.1 μm with an average PM1 of 90% of total PM mass.

*O Sippula* [45] investigated effects of chlorine and sulphur on particle formation combustion in a laboratory scale reactor (0.57 kW) fired fine wood power originating from a plywood veneer grinding process with 80% of birch. He performed four different cases of experiments such as: (A) combustion without additives, (B) combustion with 80 ppm additional HCl concentration in the input, (C) combustion with 80 ppm additional HCl and 400 ppm additional SO2 in the input, (D) combustion with 500 ppm additional SO2 in the input. The particle size distributions were measured using ELPI and SMPS after dilution tunnel and EDX was used to analyze chemical composition of the emitted particles. From the experiment it was observed that an addition of HCl increased both particle number concentration and mean particle size and thus clearly increased the fine particle mass concentration. Adding of $SO_2$ concentration had only a minor effect on the particle size distributions when no HCl was added. When both HCl and $SO_2$ were added into the reactor, particle formation seemed to be dependent on the S/Cl ratio. The PM1 mass concentrations for different cases were in average 101, 243, 166 and 225 mg/Nm$^3$ respectively. The dominating chemical compositions of fine particle were potassium, sodium, calcium, chlorine when no additive used.

*A Wierzbicka* [46] characterized particle emissions from a district heating boiler of maximum thermal output 1 MW fired with forest residues. Mass concentrations, number concentrations and their size distribution were determined after multi cyclone by SMPS and DLPI respectively. Elemental composition of the particles was analyzed by particle induced X-ray emissions (PIXE) and Transmission Electron Microscopy (TEM) analysis. PM1 mass concentration was found 85 mg/Nm$^3$, while PM1 number concentrations were 7.7 x 107 particles/Ncm$^3$. Both PM1 mass and total number concentration were dominated by submicron particles, having diameter less that 1 μm. Dominating chemical compositions in fine mode analyzed by PIXE/TEM were K, S, Cl, S, Ca, Zn.

*L Lillieblad* [47] studied load influence on boiler's operation with the emissions of fine particles from biomass combustion in a district heating boiler of thermal capacity around 1 MW fired with wood pellets. ELPI and Low Pressure Impactor (LPI) were used for the measurement of number size distributions and mass size distribution respectively and combined with particle induced X-ray emission (PIXE) for elemental analysis. The boiler load was found to have little influence on the fine particles mass concentration, which was in the range between 50 and 75 mg/Nm$^3$. The total particle number concentration increased with the increased boiler load, decreased particle size was observed at that time. He found from the elemental analysis that potassium and sulfur were the dominating components in the submicron size ranges.

*J Tissari* [48] investigated the emission characteristics from the modern masonry heater, conventional masonry heater and traditional sauna stove fired with different sizes of wood logs. The sample flow was diluted in a dilution tunnel before particle measurement and ELPI was used to measure the particle number emissions and size distributions. Dekati impactor was used to measure fine particle mass concentrations and size distributions. Elemental composition of the particles was performed by Inductively Coupled Plasma Mass Spectrometry (ICP-MS) analysis. All cases, sauna stoves emitted higher fine particle emissions and number concentration and the fly ash was mainly of alkali metal compounds such as sulphates, chlorides and carbonates.

*J Tissaria* [49] investigated field measurement method for fine particle emissions from different residential combustion appliances such as modern masonry heater, stove, baking oven, sauna stove fired with wood logs in different sizes. The measurement devices were installed inside a box and it was heated about 1.5 h before and during the measurements with a thermostat controlled heater (2 kW) and was placed near the chimney. The sampling probe was situated in the center of the chimney after the pre-cyclone of cut-off diameter 10 µm. Particle number and size distributions were measured by ELPI and SMPS after the dilution tunnel. Dekati impactor with a cut-off size 1 µm was used to ensure the removal of coarse particle and the particle measurements were combined ICP-MS for fine particle elemental analysis. He observed that the ELPI gave approximately 1.4 fold particle number emission compared with the FMPS except for the sauna stove measurement, where the particle number emissions were equal for both measurement devices. The average particle number size geometric mean diameter GMD measured with the FMPS varied from 54 to 106 nm. The particle mass concentration for sauna stove was 2-5 fold than from other appliances, while 1.4-2.3 fold for number concentrations because of poor operational practice. The dominating ash forming elements were potassium, sulfur, chlorine, zinc, aluminum, sodium and calcium.

*H Wiinikka* [50] studied the influences of particle emissions from a 10 kW updraft pellet reactor fired with three different biomass fuels (bark pellets, wood pellets, and granulates from hydrolysis residues) under identical conditions. Particulate emissions were collected from the flue gas stack with a 90 mm quartz filter and mass size and number size distribution were measured by DLPI and SMPS respectively and combined with Environmental Scanning Electron Microscopy (ESEM) for particle morphology and EDS for elemental composition. For all experimental conditions (except bark pellets), almost all mass in the measured size range was found in the submicron range (<1 µm). The particle number concentrations for all cases were in the ranged between 107-108 particles/Ncm3 and size ranged 15.4-697 nm. The dominating chemical compositions of the fine particles were K, Cl, S, Na, Fe and Zn.

*I Obernberger* [51] investigated particle emissions from a moving grate boiler (440 kW) fired with various biofuels such as spruce and bark. Characterization of particle emissions was done on the basis of Berner low pressure impactor (BLPI) and measurements were combined with SEM/EDX analyses for elemental analysis. The mass concentrations of fine particles for spruce were 20 mg/Nm$^3$, while and 60 mg/Nm$^3$ for bark fuel. Particle mass concentrations were dominated by fine mode (PM1> 90% of PM10) with an aerodynamic diameter between 0.1 µm and 0.5 µm for all cases and was highly correlated with the K, S and Cl content of the fuel.

## 6. Analysis and Summary

This literature review has been conducted based on the research articles published in the journals, conference proceedings, reports from the research institutions. The majority of the published articles reported that particle mass concentrations and size distribution were measured by DLPI and BLPI, while SMPS, ELPI and FMPS applied for number concentrations and size distributions. The selection of the particle measuring instruments is important as these instruments have specific advantages and disadvantages. The advantages of ELPI are good time resolution, which allows the observation of relatively short temporary changes or fluctuation in the process, and a wide particle size range. The advantage of SMPS and FMPS is the high size resolution of fine particles.

The extensive literature on particle formation and emissions from both laboratory and field measurement has been summarized into three categories to show how combustion appliances and fuel affect the mass concentrations, number concentrations, corresponding size distributions and chemical compositions. Particle mass concentrations data generated from different appliances have been made a graphical comparison.

### *6.1. Mass concentrations*

Mass concentrations of particles in the flue gas from small scale combustion appliances combusted wood pellets, wood chips, wood logs and forest residues have been reported in the literature to be in the range of 7-67 mg/Nm$^3$. The highest mass concentrations were reported during combustion of wood pellets in a pellet stove. Table 2 presents the summary of the particle mass concentrations and their size distributions from various combustion appliances in different fuels available in the literature. From the Table 2 it is observed that particle mass concentrations are affected by both combustion appliances and fuel parameters.

Figure 4 gives a graphical comparison of the particle mass concentrations against various combustion appliances such as pellet stoves, pellet boilers, wood chip boilers and wood log boilers. Figure 4 shows that wood chip boilers, pellet stoves, wood log boilers (except WLB-30 kW [22]) give higher emissions of particle mass concentrations compared to pellet boilers. For pellet stoves, the graph shows that particle mass concentration correlated linearly with the thermal output of the stoves.

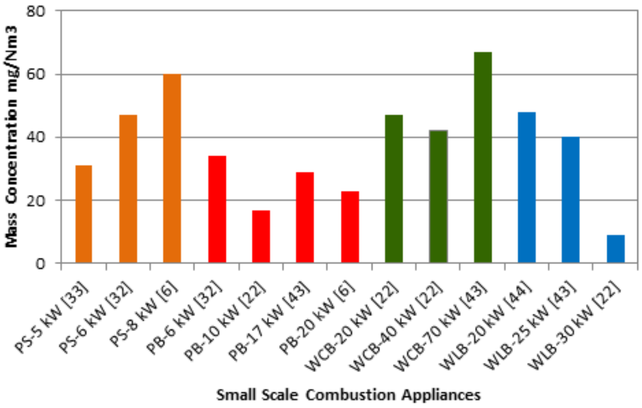

**Fig. 4.** Comparison of particle mass concentrations against small scale combustion appliances (mass concentrations are normalized in 13% oxygen concentrations, PS = Pellet stove, PB = pellet boiler, WCB = wood chip boiler, WLG = wood log boiler)

**Table 2.** Mass concentrations and their size distributions of particle emissions from small scale biomass combustion appliances (all data based on 13% oxygen concentration)

| Heating Appliances | Thermal Output (kW) | Fuel, Moisture (m, %) | Instruments used | Mass Concentration (mg/Nm$^3$) | Ref |
|---|---|---|---|---|---|
| Pellet stove | 8 | Wood pellet | Filter samples | $PM_1$: 60 | [6] |
| | 6 | Wood pellets m=7.6% | Filter samples DLPI | $PM_{10}$: 47 | [32] |
| | 5 | Pellet | Filter samples BLPI | $PM_{10}$: 31 | [33] |
| Pellet boiler | 10-15 | pellet | Glass fiber filter DLPI | $PM_1$: 89.5±7.4% of total PM | [33] |
| | 6 | Wood pellets m=7.6% | Filter samples DLPI | $PM_{10}$: 34 | [32] |
| | 20 | Wood pellet | Filter samples DLPI | $PM_1$: 23±3 | [6] |
| | 20 | Wood pellet m=7.1 % | Filter samples BLPI | $PM_{10}$: 13-18 | [22] |
| | 10 | Wood pellet m=7.1 % | Filter samples BLPI | $PM_{10}$: 14-21 | [22] |
| | 17 | Wood pellet | Filter samples | $PM_{10}$: 29±0.5 | [43] |
| | 190 | Wood pellets | Filter samples Andersen Impactors | $PM_{10}$: 33 | [41] |
| Wood chip boiler | 40 | Wood chips m=17.4% | Filter samples BLPI | $PM_{10}$: 28-56 | [22] |
| | 20 | Wood chips m=17.4% | Filter samples BLPI | $PM_{10}$: 33-61 | [22] |
| | 70 | Wood chips m=30% | Filter samples | $PM_{10}$: 67±8 | [43] |
| Wood log boiler | 30 | Wood log m=11.56% | Filter samples BLPI | $PM_{10}$: 8.8 | [22] |
| | 15 | Wood log m=11.56% | Filter samples BLPI | $PM_{10}$: 6.8 | [22] |
| | 25 | Wood log, m=20% | Filter samples | $PM_{10}$: 42±17 | [43] |
| | 20 | Wood log | Filter Sample BLPI | $PM_{10}$: 48 | [44] |
| Laboratory scale reactor | 0.57 | Wood powder | PTFE filter samples | $PM_1$: 101 | [45] |
| Moving grate boiler | 500 | Wood pellet | Filter samples DLPI | $PM_1$: 26±3 | [6] |
| | 440 | Spruce | BLPI | $PM_1$: 20 | [51] |
| | 440 | Bark | BLPI | $PM_1$: 60 | [51] |

DLPI = Dekati Low Pressure Impactor
BLPI = Berner Low Pressure Impactor
LPI = Low Pressure Impactor

### 6.2. Number concentrations

Particle number concentrations are related to the particle size. Incomplete combustion produces lower number emissions but larger particle sizes than complete combustion. Particle number concentrations in the flue gas from small scale combustion appliances reported in the literature were in the range of 0.8 x $10^7$- 5.5 x $10^9$ particles/cm$^3$. Table 3 shows a comparison of particle number concentrations and their size distributions measured from various combustion appliances fired with different fuels. Particle number distributions were mainly dominated by fine particles but dependent on combustion conditions. It is observed from Table 3 that particle number concentration and their size distribution depend on combustion appliances and fuel properties. There were also significant differences in the particle number concentration emissions from different combustion appliances. In most of the experiments, number concentrations and size distributions were measured by Scanning Mobility Particle Sizer (SMPS) followed by Electrical Low Pressure Impactor (ELPI) and First Mobility Particle Sizer (FMPS).

### 6.3. Chemical compositions

Biomass fuels have high ash contents and varying ash compositions including easily volatile elements. Chemical compositions of fine particle emissions from small scale biomass combustion reported in the literature are presented in Table 4. The dominating chemical compositions of the particle emissions were K fraction followed by S, Cl and Na and consequently dominant compounds found in the fine mode were $K_2SO_4$ and KCl. Besides the alkali metals, Zn and Fe were also reported in the literature. Fine particle formation and chemical compositions are influenced by fuel properties. Table 4 shows that most of the experiments for analyzing chemical compositions of inorganic fraction performed by the instruments Energy Dispersive X-ray Spectroscopy (EDX) followed by Scanning Electron Microscopy (SEM) and Particle Induced X-ray Emission (PIXE) and Time of Flight-Secondary Ion Mass Spectrometry (TOF-SIMS).

**Table 3.** Number concentrations and their size distributions of the particles emitted from small scale biomass combustion (all data based on 13% oxygen concentration)

| Heating Appliances | Thermal Output (kW) | Fuel Moisture (m, %) | Instruments used | Number Concentration (particles/cm$^3$) | Ref |
|---|---|---|---|---|---|
| Pellet stove | 6 | Wood pellets m=7.6% | ELPI, SMPS | $PN_{10}$: 1.8-8.8 x $10^7$ | [32] |
| | 5 | Wood pellets | SMPS | $PN_1$: 1.5-5.4 x $10^7$ | [44] |
| Pellet boiler | 6 | Wood pellets m=7.6% | ELPI, SMPS | $PN_{10}$: 1.1-4.7 x $10^7$ | [32] |
| | 20 | Wood pellet | ELPI, FMPS | $PN_1$: 1.5 x $10^8$ | [6] |
| | 17 | Wood pellet | SMPS | $PN_{0.6}$: 0.8 x $10^7$ | [43] |
| Wood chip boiler | 40 | Wood chips m=17.4% | ELPI | $PN_{10}$: 1.2-1.9 x $10^7$ | [22] |
| | 70 | Wood chips m=30% | SMPS | $PN_{0.6}$: 1.4 x $10^8$ | [43] |
| Pellet reactor | 10 | Wood pellets | | $PN_1$: $10^7$-$10^8$ | [50] |
| Wood logs boiler | 25 | Wood log m=20% | SMPS | $PN_{0.6}$: 1.8 x $10^8$ | [43] |
| | 20 | Wood log | SMPS | $PN_1$: 1.2-4.7 x $10^7$ | [44] |
| Laboratory scale reactor | 0.57 | Wood powder | SMPS | $PN_1$: 1.5-5.5 x $10^9$ | [45] |
| District heating Boiler | 1000 | Forest residues | SMPS | $PN_1$: 7.7 x $10^7$ | [46] |

ELPI = Electrical Low Pressure Impactor
SMPS = Scanning Mobility Particle Sizer
FMPS = First Mobility Particle Sizer
PN = Particle Number

$PN_{0.6}$, $PN_1$ and $PN_{10}$ refer to particle number with an aerodynamic diameter smaller than 0.6, 1, and 10 μm respectively

**Table 4.** Dominating chemical elements and compound of inorganic fraction of the fine particle emissions from small scale biomass combustion

| Heating Appliances | Thermal Output (kW) | Fuel, Moisture (m, %) | Instruments used | Dominating element | Dominating inorganic compound | Ref |
|---|---|---|---|---|---|---|
| Pellet stove | 6 | Wood pellets m=7.6% | EDX TOF-SIMS | K, S, Cl and Na | $K_2SO_4$, KCl | [32] |
| Masonry heater | - | Wood logs | SEM<br>EDX | K, S, Zn, Ca, Cl and Na | - | [42] |
| Sauna Stove | - | Wood logs | ICP-MS | Ka, Na | Alkali metal compounds -sulphates, chlorides, carbonates | [48] |
| Pellet boiler | 10-15 | Pellet | EDS | K, Cl, S, Na and Zn | KCl | [33] |
| | 6 | Wood pellets m=7.6% | EDX TOF-SIMS | K, S, Cl and Na | $K_2SO_4$, KCl | [32] |
| | 20 | Wood pellets, m=7.1% | SEM EDX | K, S, Cl, Na | $K_2SO_4$, KCl | [22] |
| | 190 | Wood pellets | ICP-OES | K, S, Ca, Na | - | [41] |
| Wood chip boiler | 40 | Wood chips m=17.4% | SEM EDX | K, S, Cl, Na | $K_2SO_4$, KCl | [22] |
| Wood log boiler | 30 | Log wood m=11.56% | SEM EDX | K, S, Cl, Na | $K_2SO_4$,KCl | [22] |
| Moving grate boiler | 440 | Bark, spruce | SEM EDX | K, S, Cl | - | [51] |
| Pellet reactor | 10 | Wood pellets | ESEM EDX | K, Cl, S, Na, Fe, and Zn | - | [50] |
| Laboratory scale reactor | 0.57 | Wood powder | EDX | K, Na, Ca and Cl | - | [45] |
| District heating boiler | 1000 | Forest residues | PIXE TEM | K, S, Cl, Ca, Zn | - | [46] |
| | 1000 | Wood pellet m=7.3% | PIXE | K, S | - | [47] |

EDX = Energy Dispersive X-ray Spectroscopy
SEM = Scanning Electron Microscopy
ICP-MS = Inductively Coupled Plasma-Mass Spectrometry
EDS = Energy Dispersive Spectroscopy
TOF-SIMS = Time of Flight-Secondary Ion Mass Spectrometry
ICP-OES = Inductively Coupled Plasma-Optical Emission Spectrometry
ESEM = Environmental Scanning Electron Microscopy
PIXE = Particle Induced X-ray Emissions
TEM = Transmission Electron Microscopy

## 7. Conclusion

Particle emissions characteristics of small scale biomass combustion from different appliances have been gathered and reviewed from the recent studies available in the literature. Combustion appliances consist of pellet stove, pellet boiler, wood chip boiler, wood log boiler and different fuels such as wood pellets, wood chips, wood logs and forest residues were fired in these appliances. From the literature, it is clear that particle formation and emission is closely related not only to the fuel properties but also to the combustion conditions and processes of the furnace. Following conclusions can be drawn from the literature review.

- Soot and organic particles are formed due to incomplete combustion conditions, while ash particles are non combustible material introduced into the furnace.
- The selection of the particle measuring instruments is important as these instruments have specific advantages and disadvantages. The advantages of ELPI are good time resolution, which allows the observation of relatively short temporary changes or fluctuation in the process, and a wide particle size range. The advantage of SMPS and FMPS is the high size resolution of fine particles.
- Particle mass concentrations were reported in the range of 7-67 mg/Nm3. Particle number concentrations were found in the range of 0.8 x 107-5.5 x 109 particles/cm3.
- The dominating chemical compositions of the particle emissions were K fraction followed by S, Cl and Na and consequently dominant compounds found in the fine mode were K2SO4 and KCl.
- Biomass fuels have high ash contents and varying ash compositions, including problematic elements such as potassium, chlorine, sulphur, sodium and zinc. This may lead to high emissions, especially fine particle emissions, as well as operational problems.

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## Nomenclature:

| | |
|---|---|
| nm: | nanometer |
| µm: | micrometer |
| APSS: | Aerodynamic Particle Sizer Spectrometer |
| BLPI: | Berner Low Pressure Impactor |
| DLPI: | Dekati Low Pressure Impactor |
| EDS: | Energy Dispersive Spectroscopy |
| EDX: | Energy Dispersive X-ray Spectroscopy |
| ELPI+: | Electrical Low Pressure Impactor Plus |
| ELPI: | Electrical Low Pressure Impactor |
| ESEM: | Environmental Scanning Electron Microscopy |
| FMPS: | First Mobility Particle Sizer |
| ICP-MS: | Inductively Coupled Plasma-Mass Spectrometry |
| ICP-OES: | Inductively Coupled Plasma-Optical Emission Spectrometry |
| PIXE: | Particle Induced X-ray Emissions |
| PAH: | Polycyclic Aromatic Hydrocarbons |
| PM: | Particulate Matter |
| SEM: | Scanning Electron Microscopy |
| SMPS: | Scanning Mobility Particle Sizer |
| TEOM: | Tapered Element Oscillating Micro Balance |
| TEM: | Transmission Electron Microscopy |
| TOF-SIMS: | Time of Flight-Secondary Ion Mass Spectrometry |
| VOC: | Volatile Organic Compounds |

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