

# An Overview of PM Formation Mechanisms from Residential Biomass Combustion and Instruments Using in PM Measurements

M. Obaidullah\*, S. Bram and J. De Ruyck

**Abstract**— Residential biomass combustion produces huge amounts of fine particles that may lead to high flue gas emissions and consequent adverse health effects. Emissions of pollutants from residential biomass combustion appliances vary over a wide range depending on the combustion technology and on the quality of the combustion and fuels used. This review discusses an overview of particulate matter (PM) formation mechanisms from residential biomass combustion. It includes classification of particles with different categories and their formation pathways. Formation mechanisms of soot, organic and ash particles are discussed elaborately. Characteristics of biomass fuels and their chemical compositions which lead to PM formation are also discussed. Widely used particle sampling methods, state of the art instruments, full flow and partial flow dilution systems related to PM measurements are also discussed here. Advantages and disadvantages of PM measuring instruments are compared. From the review, it is observed that PM emission is not only closely related to the fuel properties but also to the combustion circumstances in the furnace and operating conditions. The measurement done by each instrument has its own principle and technique. Therefore, the selection of the particle measuring instruments is very important because different instruments have different advantages and disadvantages. This review can help the academicians and the researchers to choose the most appropriate instruments in particle sampling and measurements from residential biomass combustion.

**Keywords**—particulate matter, residential biomass combustion formation mechanisms, measurement methods, instruments.

## I. INTRODUCTION

Biomass is seen as one of the options to mitigate greenhouse gas emissions and substitute fossil fuels. There is a growing interest using of biomass fuels for energy production purposes across the world. Heat from biomass combustion is the oldest and, still today, a widely applied energy source for a variety of applications, such as heating, power production and cooking. Residential biomass combustion for heating purposes is carried

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out in simple wood stoves as well as in well-controlled devices, such as pellet burners and modern wood boilers. Emissions of pollutants from these appliances vary over a wide range depending on the technology of the combustion furnace and on the quality of the combustion and biofuels used. The combustion of biomass fuels in small scale heating appliances is a major source of fine particulate matter (PM) emissions. These appliances are accused of producing harmful particulate pollutants, since they generate significant amounts of particles at low emission heights.

Biomass combustion is one of the major contributors of fine particles to the atmosphere during winter times over large parts of Europe and small-scale combustion systems in particular play an important role [1-3]. Concerning PM emissions, epidemiological and experimental studies evidence a correlation between biomass combustion particles and health impacts like decreased lung function, reduced resistance to infections and increased incidences of acute asthma [4-7]. Exposure to biomass smoke could also induce cardiovascular effects [4, 5, 8].

People can be exposed to particulate matter in indoor or outdoor environments. Utell et al. [13] mentioned that particulate number concentrations can vary from 5000 to 10,000 particles/cm<sup>3</sup> in outdoor air [9]. This number concentration can increase from 300,000 particles/cm<sup>3</sup> to 1,000,000 particles/cm<sup>3</sup> during winter time. Li *et al.* [6] reported that particles with diameter less than 1 μm are the most harmful to human health and most contributed to air pollution in urban areas. Cofala et al. [10] cited that dominating source of PM<sub>2.5</sub> from the combustion of solid biomass was about 34 % to the total emissions in EU-27 countries. Recent investigations show that biomass combustion contributes more than 20 % of carbonaceous aerosols in France during winter months [11].

Measurement and sampling of particles from biomass combustion appliances is very challenging. The particle size range is wide, and the flue gas contains particles that vary from a few nanometers (nm) to several micrometers (μm) in size [2]. There are different state of the art instruments available using for measuring PM emissions characteristics from small scale combustion appliances. These instruments work in real time with different principles. The significant PM measurement characteristics are mass concentrations, number concentrations and their particle size distributions. PM emission measurements conducted using different instruments

from residential biomass combustion are reported in several studies [1, 6, 12, 13]. In addition, measurements of particles can vary widely, even those made for the same material and in the same place. This variation is mainly caused by the instruments used for measuring particles and the sampling procedures. There are many challenges related to PM measurements, but still need to be quantified to control emission level in order to improve the air quality. However, sufficient information regarding PM formation mechanisms from residential biomass combustion and instruments using in PM measurements is usually not found in the literature

This review presents the characteristics of biomass fuels and their chemical compositions which lead to particle formation. Brief overview of particle formation from residential biomass combustion are also discussed. As particle emission is one of the major concerns associated with small scale biomass heating systems, formation mechanisms of soot, organic and ash particles are discussed elaborately. It includes classification of particles and their formation pathways. Widely used particle sampling methods and state of the art instruments, full flow and partial flow dilution systems related to particle measurements are also discussed in this review article.

## II. CHARACTERISTICS OF BIOMASS FUELS

Biomass fuels are biological materials derived from various living organisms. Emissions from biomass combustion are considered to be CO<sub>2</sub> neutral regarding the global carbon cycle. This is because the CO<sub>2</sub> emitted during biomass combustion is considered to be equal to the CO<sub>2</sub> absorbed by the trees during the photosynthesis and similar to the amount of pollutant that would be emitted during the natural decay of the wood. This is considered to be the main environmental benefit of biomass combustion and the main advantage of biomass compared to fossil fuels. The most common sources of biomass fuels are trees (e.g. forest residues) and cultivated plants (e.g. straw) [14, 15]. Different forms of biomass fuels such as wood logs, wood chips, wood pellets, saw dust, forest residues, straw etc. are used as fuels in small scale combustion appliances.

Softwood is commonly used in small scale biomass combustion appliances. Typical properties of soft wood is about 50 % cellulose, 23 % hemicelluloses, 22 % (soft) lignin and 5 % other. The composition (by mass) of carbon, hydrogen, oxygen, nitrogen and mineral ash are about 48 %, 5.9 %, 44 %, 0.5 % and 1.6 % respectively. In contrast to many other fuels, the volatile matter content of biomass fuel is high typically 82 % by dry weight and fixed carbon is about 16 % [14-16]. The higher heating value is close to 20 MJ/kg, the lower heating value (dry biomass) around 18 MJ/kg.

Biomass fuels also contain 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 [17, 18]. Although the characteristics of biomass fuels vary largely, in general there are some common properties which make them considerably different from fossil

solid fuels. These differences also play an important role in relation to particle formation during combustion.

## III. PM FORMATION MECHANISMS

The combustion of biomass fuels can result in a broad range of potential pollutants. It leads to the formation of gaseous and particulate matter (PM) pollutants that have negative impact on ambient air quality and the environment. This review mainly focuses on the formation of PM emissions. PM is a dynamic mixture of particles in the flue gas released from the combustion devices. Particle emissions originate from several sources and are related to the properties of fuels, the combustion conditions, the air fuel ratio. Various classifications and terminologies can be seen in the literature to define particle size ranges.

### A. Classification by Size

Particles can be divided into two groups under this category [2]. These are fine particles and coarse particles. Particles smaller than 1 µm (micro meter) in diameter are often called fine particles. 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 often called coarse particles, forming mainly from char or ash species with low vapour pressures which do not vaporize during combustion [19, 20]. PM<sub>1</sub>, PM<sub>2.5</sub> and PM<sub>10</sub> fractions refer to mass concentrations of particles smaller than 1, 2.5 and 10 µm. PM<sub>1</sub> and PM<sub>2.5</sub> are the most harmful for people as the particles can penetrate deep into the lungs. These particle sizes are always related to the aerodynamic diameter which represents the diameter of a spherical particle with a density of 1000 kg/m<sup>3</sup> having the same drag in air as the particle of interest [15, 21, 22].

### A. Classification by Formation Pathways

Particle formation can be classified into three modes. These are nucleation mode, accumulation mode and coarse mode. These modes correspond to peaks within the particle size distributions. The location of such modes is variable depending on the specific sources and formation pathways as shown in Figure 1 [23].

Besides, the formation modes, combustion particles from biomass fuels can be divided into primary and secondary particles. Primary particles form at high temperatures in the combustion zone and secondary particles form both in the flue gas exhaust and in the atmosphere. There are mainly three sources of primary particles as given below according to origin and formation mechanisms, and these particles are emitted directly to the ambient air from the combustion appliances [15, 19, 24-27]. 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.

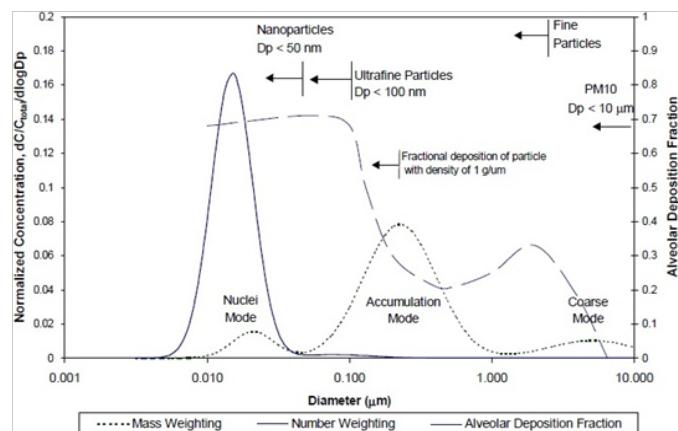


Fig. 1 Common definitions of particle size ranges and typical size distributions for combustion particles

### B. Formation Pathways of Primary Particles

The following sections briefly present the formation pathways of different types of primary particles.

**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 information in the literature 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.

Generally, two pathways for the formation of soot nuclei can be discussed. First, at lower temperatures, aromatic hydrocarbons produce soot directly by growing into graphite-like structure. Second, at higher temperatures both aliphatic and aromatic hydrocarbons first fragment, which are followed by polymerization of the fragments to larger molecules, forming soot. Thereafter, the particles grow larger by surface reactions, coagulation and agglomeration [15, 17, 26, 28]. The resulting soot particles are thus composed of smaller spherical particles as shown in Figure 2 [17, 28].

The formation process depends mainly on the fuels, 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 [15, 26].

**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. 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 from the flue gas.

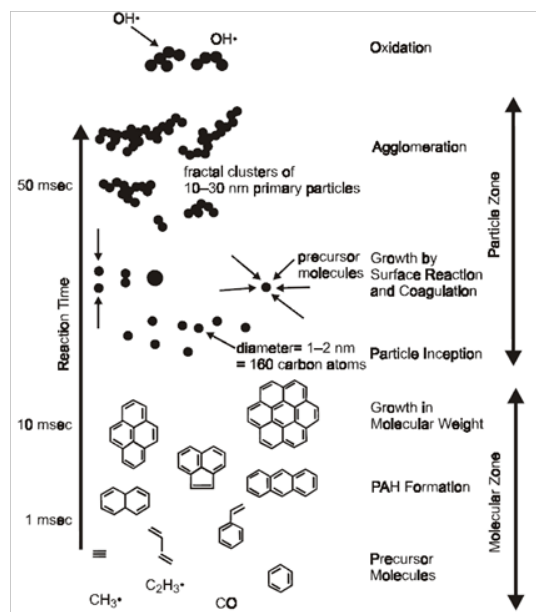


Fig. 2 Schematic of soot formation [29]

Poor combustion conditions can also be associated with natural fires that are a large source of organic matter in the atmosphere [25]. They are typically divided according to their boiling points into very volatile organic compound (VVOC), volatile organic compound (VOC) and semi volatile organic compound (SVOC) and particle phase compounds (POM). Incomplete biomass combustion produces hundreds of different organic compounds [25, 27]. 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 [21, 30].

**Formation of ash particles:** Solid fuels such as biomass contain considerable amounts of ash forming inorganic elements [17]. 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. The release of ash compounds is generally connected to combustion temperatures. Ash forming species in biomass fuels can be divided into three categories [2, 15, 17, 19, 26], 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) and (iii) easily volatile heavy metals like zinc (Zn), lead (Pb), cadmium (Cd), etc.

The major share of the ashes formed during biomass combustion staying in the furnace is 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 ash particles ( $>1 \mu\text{m}$ ). These coarse fly ash emissions are in a particle size range between some  $\mu\text{m}$  to about several  $\mu\text{m}$  [2, 25, 26].

The particle formation pathways during biomass combustion under fixed bed conditions are shown in Figure 3 [15, 20]. Part of the inorganic elements contained in the fuel may be released and form inorganic gas species and particulate matter. It can be seen from Figure 3 that the particulate matter can be formed by different pathways, which lead to a characteristic bimodal particle size distribution. One is the fine mode ( $< 1 \mu\text{m}$ ), in which the main route of particle formation is nucleation and condensation from the gas phase. The other is the coarse mode ( $>1 \mu\text{m}$ ), 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  $\text{K}_2\text{SO}_4$  (potassium sulphate),  $\text{KCl}$  (potassium chloride),  $\text{K}_2\text{CO}_3$  (potassium carbonate) and smaller amounts of zinc, sodium and organic material.

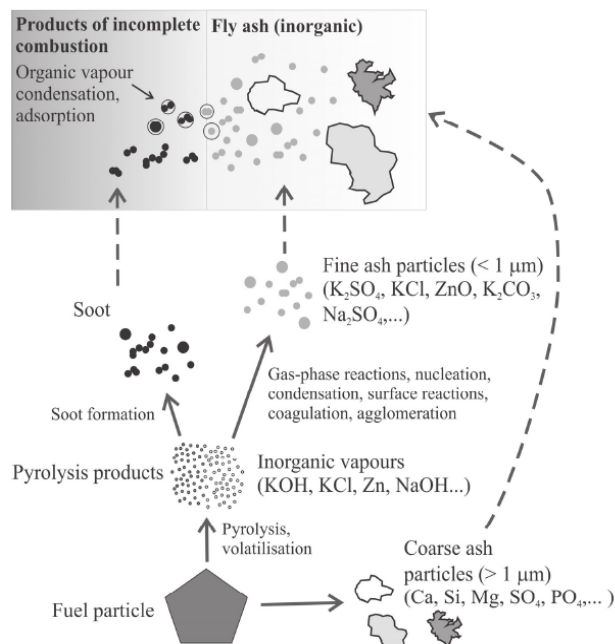


Fig. 3 Particle formation pathways from biomass combustion [15, 20]

**Particle Characteristics:** The particle emissions characteristics available in the literature are discussed in terms of the following parameters [5, 15, 29, 31-33].

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

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. The size is already defined in Section III A. 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 for mass and number concentrations are  $\text{mg}/\text{Nm}^3$  and  $\text{particles}/\text{cm}^3$  respectively. Chemical characteristics related mainly to chemical constituents include elements, morphology, shape and organic compounds of particulate matter.

#### IV. INSTRUMENTS USING IN PM MEASUREMENTS

The measurement of particles from biomass combustion appliances is very challenging. The particle size range is wide, and the flue gas contains particles that vary from a few nanometers (nm) to several micrometers ( $\mu\text{m}$ ) in size. Sampling is subject to kinetic and chemical effects which tend to bias the results. Measurement of particle concentrations both in number and mass from the combustion devices are important for regulatory and scientific reasons. There are many technologies available to determine particle concentrations and size distribution from these sources.

Measurements of particles are conducted in terms of mass concentrations, number concentrations and their size distributions. There are several measurement instruments available for real time measurements of particle characteristics. The selection of the measuring instruments for particle emissions and their size distributions is very 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.

- 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 Microbalance (TEOM)

The above instruments for characterizing particle emissions work based on the principle of gravimetric, optical, mobility and aerodynamic effects, leading to several equivalent particle diameters such as the optical, the mobility or the aerodynamic diameter. The following sections discuss some of the most widely accepted techniques.

##### A. Gravimetric Method

This method is commonly used to measure mass concentrations of particulate matter in flue gases using quartz or glass filters. Filters are weighed under controlled temperature and relative humidity conditions before and after sampling. This method gives total mass concentration. In this method, a filter sample from a well defined volume of exhaust gas is taken. The filter is weighted before and after taking the sample. To avoid errors by water take-up of the filter, it is important to always condition it at a certain humidity before



weighting. The physics of particle collection by filters is similar for all types of filters. Particles smaller than about  $0.1 \mu\text{m}$  are collected by diffusion [34]. Because particle diffusivities increase with decreasing size, collection efficiencies increase as size drops below approximately  $0.1 \mu\text{m}$ . Particles larger than about  $0.5 \mu\text{m}$  are collected by interception and impaction. Collection efficiencies for these mechanisms increase with increasing size. Therefore, collection efficiencies tend to increase with increasing size above  $0.5 \mu\text{m}$  [34]. Particles collected on the filter are potentially available for additional chemical analysis.

It is found in the literature that concentration of PM mass can be varied, depending on the conditioning conditions of the filter. For this reason, the studies emphasized that the filters are usually packed under controlled conditions of temperature and relative humidity [33, 35, 36].

### B. Optical Method

The optical method is widely used for particle detection and measurement in various fields such as monitoring of particle levels and environmental control. This method measures the scattered light, which is proportional to the volume concentration of the particles. This is achieved by directing the sample particles flow across a light beam and by collecting a portion of the scattered light into a detector. Figure 4 shows the working principle of the optical method [37]. Particle number concentration is measured in real time by optical particle counters (OPCs) based on the principle of light scattered by single particles. Each particle traversing the light beam results in a detector signal at the output and the number  $n$  of signals during a certain time  $t_p$  is proportional to the particle concentration  $N$  according to the following formula, where  $Q$  is the volume flow rate of the sample.

$$N = \frac{n}{Q \cdot t_p} \quad (1)$$

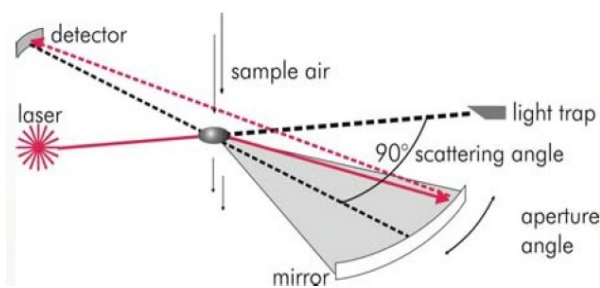


Fig. 4 Schematic illustration of optical method

Aerodynamic Particle Size Spectrometer (APSS) is the instrument working with this principle. APSS is capable to measure larger particle size in the range of  $0.5$  to  $20 \mu\text{m}$ .

### C. Mobility Method

For the mobility method, particles first have to be charged. A mobility spectrometer consists of a charger, a differential mobility analyzer (DMA) and a particle counter. The schematic of the differential mobility analyzer is shown in Figure 5 [38]. By setting different voltages in the DMA,

particles of different electrical mobility are selected and their particle number concentration can be measured. The DMA consists of two electrodes with the inner electrode at a negative voltage, while the outer electrode is electrically grounded. This creates an electric field between the two electrodes. Before entering the DMA, the sample particles are charged by passing through the charger, where positive and negative ions are produced. The charged aerosols are introduced through an annular slit closed to the outer electrode into the top of the DMA and then, merged with the particle free air flow. The flow of both streams is maintained in the laminar regime to prevent mixing of those streams. In the DMA, charged particles are separated according to their electrical mobility. The electrical particle mobility is a function of the particle charge, particle diameter, dimensions of the DMA, and the flow rate. The sample flow carrying particles with the same small range of electrical mobility is drawn through the small slit located at the bottom of the collector rod. The remaining air is exhausted out as excess air flow. The particle number concentration in the sample flow is measured in a particle counter. The Scanning Mobility Particle Sizer (SMPS) and the First Mobility Particle Sizer (FMPS) are examples of the instrument working with this method. SMPS and FMPS instruments are capable to measure very smaller particles and used in health related studies to characterize ultrafine particles. These instruments are not suitable to measure larger particles.

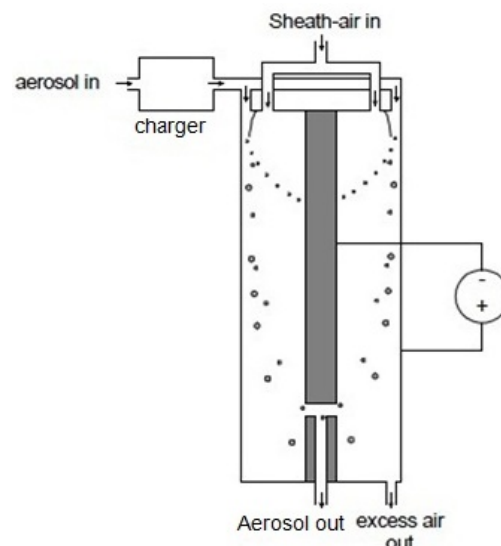


Fig. 5 Schematic illustration of differential mobility analyzer

### D. Aerodynamic Method

This principle is based on charging, inertial classification and electrical detection of the sample particles. When particles are rapidly accelerated through a nozzle, particles tend to lag behind the carrier gas due to inertia. The difference between the particle and gas speeds increases with the size and the density since inertia increases with these properties. Multistage impactors of different sizes are used under this method for sizing of particles according to their aerodynamic diameters. Electrical Low Pressure Impactor Plus (ELPI+), Electrical

Low Pressure Impactor (ELPI), Dekati Low Pressure Impactor (DLPI) are the spectrometers that work with this principal. ELPI+ is a widely used instrument for particle sampling measurements with accurate size distributions ranging from 6 nm to 10  $\mu\text{m}$ . Figure 6 shows the working principle of the ELPI+ instrument. Sample particles entering the ELPI+ are first positively charged in the charger. After being charged, the particles are introduced in the cascade impactor in order to be separated on the basis of their inertia and their aerodynamic diameter. The charged particles collected in each impactor stage produce an electrical current which is recorded by the respective electrometer. This measured current at any stage is proportional to particle concentrations.

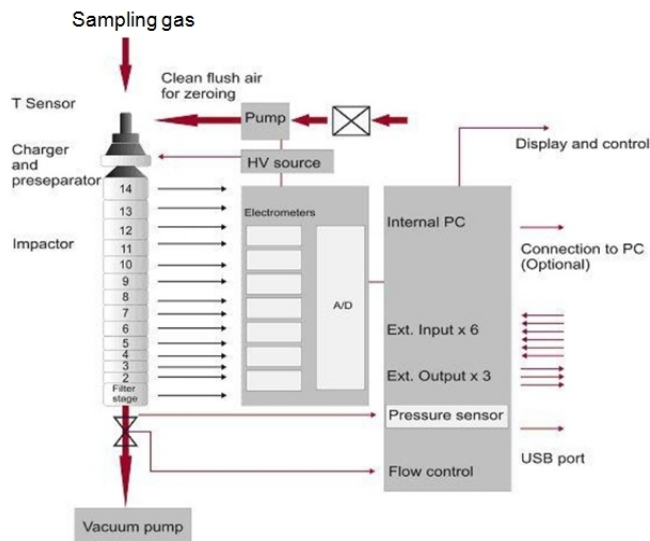


Fig. 6 Schematic illustration of the ELPI+ instrument [39]

### E. Resonance Frequency Method

Particles are collected on a filter which is located in the free end of a shallow and narrowing tube, whereas the other end of the tube is rigid and attached to the instrument. The free end of the tube is oscillated at its resonance frequency, which is strongly dependent on tube's mass. As the particles deposit on the filter, its mass increases and the oscillating frequency decreases. The change in the frequency combined with the sample volume is converted to particle mass concentration. There are two main measurement instruments that use particle measurement through resonance frequency method: Tapered Element Oscillation Microbalance (TEOM) and Quartz Crystal Microbalance (QCM). TEOM is an instrument for measuring real time total particle mass concentration. Nussbaumer et al. [33] mentioned that TEOM is a useful instrument when there is a need of  $\text{PM}_{10}$  and  $\text{PM}_{2.5}$  measurements in real time from biomass combustion. This instrument was also used in PM measurements in other studies [40, 41]. In Quartz crystal microbalance, the quartz crystal has a piezo-electric property of changing its resonance frequency when particles are deposited by electrostatic precipitation in a fine quartz crystal resonator [35].

## V. SAMPLING AND DILUTION SYSTEMS

Traditionally, emission measurements are performed in undiluted hot flue gases at temperatures of about 120-280  $^{\circ}\text{C}$ . However, sampling in raw hot flue gases may suffer from transient conditions with varying flue gas flows, or from the condensable nature of many of the semi-volatile organic compounds. This may lead to erroneous results and incorrect conclusions. In the case of particulate matter in particular, interactions between particles and walls must be limited, and appropriate quenching should be done in order to preserve both primary and secondary particle distributions. Dilution of the exhaust gas decreases the temperature and partial vapour pressures. This causes some of the semi-volatile compounds to condense on the particles. If particles are sampled from a hot and undiluted exhaust, many organic species remain in the gas phase whereas by using dilution, a fraction of the organics condenses and is collected [25, 42, 43]. Therefore, sampling at lower temperature is desirable and dilution of the hot exhaust gases is a suitable alternative method. Using a dilution tunnel in particle sampling leads to cooling of the sample gas, keeping the concentrations within the measuring range, providing possibility for long term measurements and including the organic species [25, 42, 43].

Adding to this the fact that particle measuring instruments (ELPI, ELPI+, SMPS, FMPS) cannot withstand the hot and humid flue gas for direct analysis, the use of a dilution system is obligatory in PM measurement. There are two types of dilution systems in use: full flow dilution and partial flow dilution.

**Full flow dilution:** In this tunnel, all the exhaust gases from the combustion appliance are drawn by a constant volume pump through a collection hood and are mixed with ambient dilution air. Next, the diluted exhaust gas sample passes through the filters and measuring instruments to prepare for PM sampling. With this sampling method, the size of the dilution tunnel is dependent on the volume flow of the exhaust gas. Therefore, the greater the volume flow of the exhaust gas from the combustion test unit, the larger the dilution system must be. The full flow system is quite large in size and expensive. This tunnel is steady state and not suitable for field measurements.

**Partial flow dilution:** In the partial flow system, only a small part of the exhaust gas from the combustion appliance is drawn to a dilution tunnel and is mixed with dilution air. The diluted sample passes through the analyzer for particle analysis. A number of partial flow dilution tunnels are available, including a combination of porous tube diluter (PRD) and ejector diluter (ED), ejector diluter only, two stage of ejector diluters. These tunnels are produced by different manufacturers for example Dekati Ltd., Venacontra Ltd., Horiba Ltd., etc. The PRD mainly aims at reducing particle-particle and particle-wall interactions, whereas the ED quenches the mixture by reducing the temperature to nearly atmospheric [43, 44]. The ejector diluter also works as a pump in the dilution system. Figures 7 and 8 show the schematic of the PRD and ED [44].

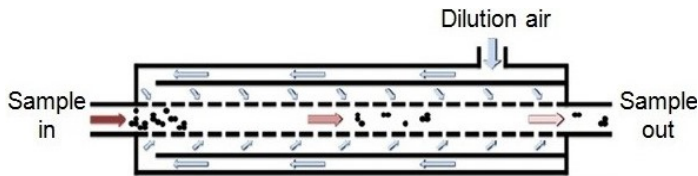


Fig. 7: A scheme of the porous tube diluter (PRD)

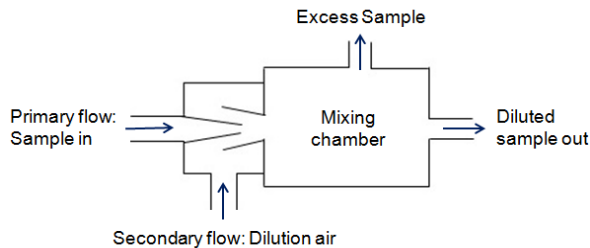


Fig. 8: A scheme of the ejector diluter (ED)

## VI. DISCUSSIONS

PM formation mechanisms from residential biomass combustion and state of the art instruments used in PM measurements are discussed in this review.

### A. Particle Formation Mechanisms

Various classifications and terminologies are discussed in this review to define particle size ranges. According to size particles are divided into two groups: fine and coarse particles. Coarse particles are formed mainly from char or ash species with low vapour pressures which do not vaporize during combustion. Fine particles ( $<1 \mu\text{m}$ ) are formed from the easily volatile inorganic elements, released from the biomass fuels to the gas phase during combustion. Potassium, sulphur and chlorine are the most relevant elements during the combustion of biomass fuels whereas sodium and heavy metals (zinc and lead) provide minor contributions. In the gas phase, these species undergo several reactions resulting in the formation of alkaline (K, Na) metal chlorides, sulphates, carbonates, and heavy metals oxides [15, 17, 19, 26]. These fine ash particles are formed by nucleation, condensation, surface reactions, coagulation and agglomerations.

Particles formed from biomass combustion are also classified into two groups: primary and secondary particles. Primary particles are formed at high temperatures in the combustion zone, whereas secondary particles are formed in the exhaust plume and the atmosphere.

Formation of primary particles are discussed elaborately in this review. There are mainly three types of primary particles: These are soot particles, organic particles and ash particles – and the formation of these particles varies with combustion conditions, fuel properties and type of appliances [2, 3, 13, 45]. Soot and organic particles originate from combustible material, whereas inorganic particles are originated from the ash content of the fuel. In residential biomass combustion appliances, soot is a large fraction of the fine particle emissions due to non-optimal combustion conditions. Operating conditions have also an important effect as soot and organic particles are formed in poorly oxygenated environments.

Inorganic elements such as Cl, K and S from biomass combustion release above  $500^\circ\text{C}$ , below  $700^\circ\text{C}$  and  $500^\circ\text{C}$  respectively [28]. Wiinikka et al. [46] observed that the formation of combustion 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.

Particle emissions from biomass combustion is also influence on the operational performance of the combustion devices. A fraction of these particles deposits on the surfaces of the combustion appliances, causing operational problems such as corrosion, fouling and as a result reduced combustion efficiency [5, 15, 21, 29, 31-33, 47-51]. 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 [15, 21, 52, 53]. These effects are also strongly dependent on the chemical properties of particles.

### B. Instruments Using in PM Measurements

A comparison among the particle measuring state of the art instruments is presented in Table 1. This comparison can help the researchers to choose the most appropriate instruments for PM sampling and measurements. Different measurement methods, advantages and disadvantages of the state of the art instruments are also evaluated in Table 1.

The majority of the published articles reported that particle mass concentrations and size distributions [15, 19, 29, 30, 54, 55] were measured by DLPI and BLPI, while SMPS, ELPI and FMPS were applied for number concentrations and size distributions [15, 19, 29, 54, 56-58]. The selection of the particle measuring instruments is important as these instruments have specific advantages and disadvantages. With the ELPI+ and ELPI, the particles are sized classified based on inertia impaction, while the SMPS and FMPS are based on the electrical mobility. 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 advantages of SMPS and FMPS are the high size resolution of fine particles. SMPS and FMPS instruments are capable to measure very smaller particles and used in health related studies to characterize ultrafine particles. Particle sampling in real-time is a desirable characteristic in all studies because it allows processes such as combustion condition to be monitored. In addition, sampling instruments that enable particle collection in real time usually have an automated system for storing data.

When designing the particle sampling train, one has to take in consideration the different operating conditions of each instrument (sample flow rate, pressure, temperature). In some cases, a cyclone has to be placed at the upstream of the measuring instrument when a size cutting is intended.

Nussbaumer et al. [33] cited a comparison of number size distributions obtained with different measurement instruments

at simultaneous measurement in flue gas from a residential biomass combustion shown in Figure 9 [56]. In the submicron range (particle size  $<0.5 \mu\text{m}$ ), ELPI, DLPI and SMPS measurements show a reasonable agreement. Above a particle size of  $0.5 \mu\text{m}$ , DLPI and APS measurements show a similar trend of a steep decrease of concentration of larger particles, in contrast to ELPI. Concentrations differ in several orders of magnitude – the highest concentrations are measured by ELPI, followed by DLPI and APSS. During successive separation in the ELPI, a minor carryover of small particles are transported from smaller size sections to larger size sections, which can lead to an overestimation of the number of larger particles.

**Table 1.** Comparison of different instruments for particle measurement [2, 3, 59, 60]

| Parameters                     | ELPI+   | ELPI                     | APSS                               | SMPS                              | FMPS                        | DLPI                               | TEOM   |
|--------------------------------|---|--------------------------|------------------------------------|-----------------------------------|-----------------------------|------------------------------------|--|
| Method                         | Aerodynamic   | Aerodynamic              | Optical                            | Mobility                          | Mobility                    | Aerodynamic                        | Resonance  |
| Size range                     | 6 nm to 10 $\mu\text{m}$  | 7 nm to 10 $\mu\text{m}$ | 500 nm to 20 $\mu\text{m}$         | 2.5 nm to 1 $\mu\text{m}$         | 5.6 nm to 560 $\mu\text{m}$ | 30 nm to 10 $\mu\text{m}$          | 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<br>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                               | NCS                               | 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 replacing 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

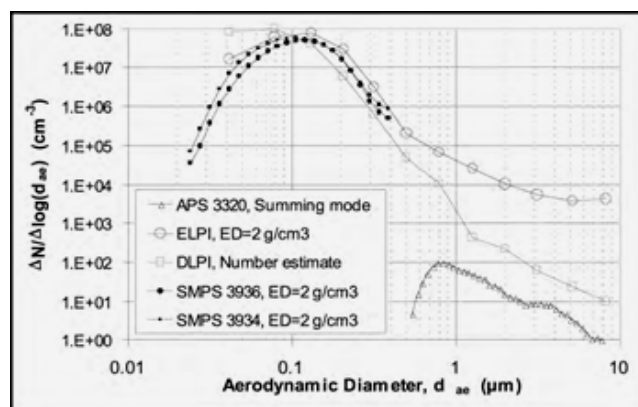


Fig. 9: Comparison of particle number concentration and number size distributions with different instruments at simultaneous measurement in the flue gas from a residential pellet burner [33], (ELPI = Electrical Low Pressure Impactor, DLPI=Dekati low pressure impactor, APS = Aerodynamic Particle Spectrometer, SMPS = Scanning Mobility Particle Sizer, ED = equivalent density)

Different dilution systems for particle sampling were also discussed. Full flow dilution tunnel is depended on the exhaust gas volume. Therefore, the greater the volume of the exhaust gas from the combustion test unit, the larger the dilution system must be. A full flow system is quite large in size and expensive. This tunnel is suited for steady state measurements and is not suitable for field measurements. The partial flow dilution tunnel can eliminate this problem by sampling a part of the total exhaust flow.

A partial flow dilution system with a combination of a porous tube diluter and an ejector diluter yields very stable conditions, which allows for the possibility to add or remove objects downstream without affecting the dilution ratio. Flow control is therefore more easy and an advantage in field measurements. After the porous tube diluter, the sample is mixed efficiently in the ejector diluter. Higher dilution ratios are possible due to additional dilution by the ejector diluter [61]. The one stage ejector diluter in combination with heated dilution air gives a low dilution ratio. The drawback of using only ED is that the dilution ratio is more or less fixed and the sample is subject to considerable particle losses due to temperature difference (thermophoresis and condensation of vapors). In addition, the ejector nozzle starts to accumulate particle deposits which affects the flow rates and sometimes also gets blocked [61]. A combination of two ejectors can be rather unstable with changing dilution ratios.



## VII. CONCLUSIONS

This review discusses particle formation mechanisms from biomass combustion and state of the art instruments working with different approaches such as gravimetric, optical, mobility and aerodynamic techniques for particle measurements. Following conclusions can be drawn from this review.

- Formation of soot, organic and ash particles varies with combustion conditions, fuel properties and type of appliances. Soot and organic particles originate from combustible material, whereas ash particles are originated from the ash content of the fuel.
- The fine particles (<1 µm) are formed from the easily volatile inorganic elements, released from the biomass fuels to the gas phase during combustion. Potassium, sulphur and chlorine are the most relevant element during the combustion of biomass fuels.
- Biomass fuels have high ash contents and varying ash compositions, including easily volatile elements such as potassium, sulphur, chlorine, sodium and zinc. This may lead to high emissions, especially fine particle emissions, as well as operational problems.
- The measurement done by each instrument has its own principle and technique. Therefore, the selection of the particle measuring instruments is very important because different instruments have different advantages and disadvantages.
- With the ELPI+ and ELPI, the particles are sized classified based on inertia impaction, while the SMPS and FMPS are based on the electrical mobility. The advantages of the ELPI+ and ELPI are a good time resolution and a wider particle size range. The advantages of SMPS and FMPS are the high size resolution of fine particles.
- Full flow dilution system is depended on the exhaust gas volume. Therefore, the greater the volume of the exhaust gas from the combustion test unit, the larger the dilution system must be. A full flow system is quite large in size and expensive. This tunnel is suited for steady state measurements and is not suitable for field measurements. The partial flow dilution system can eliminate this problem by sampling a part of the total exhaust flow.
- The combination of a porous tube and an ejector diluter is considered as the best option to reproduce the exhaust PM emissions, maintaining the particles distributions as they are when leaving the stack.

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