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Aerosol mass concentration measurements: Recent advancements of real-time nano/micro systems

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ABSTRACT

As excessive exposure to airborne particulate matter (PM) results in adverse health effects, the development of real-time PM monitoring is highly relevant. The objective of this article is to broadly review the current state-of-the-art on aerosol mass-concentration measurement, and on real-time monitoring systems. Widely used systems are bulky, time consuming or expensive to maintain. Over the past decade, sensor developments have shown the following features: portable, inexpensive, and suitable for monitoring real-time measurements. PM monitoring systems can be easily accessed through the development of nano or micro scale systems. These sensors can be integrated into conventional electronic devices in order to demonstrate their capabilities to provide real-time and ultra-sensitive measurements. However, reducing the size of the systems reveals strengths and limitations. With respect to mass concentration measurement, we distinguish a generation of “first” and “second” systems based on their different sizes. We examine the main characteristics of PM systems as follows: type of instrument devices (either bulky or nano/microfabricated), sampling method, real-time monitoring measurement capability, sensitivity, and reliability of the new generation of sensors. Acoustic mass sensors are compared to nano and micro scale electromechanical sensors. While the miniature sensors still need to be matured and integrated into appropriate aerosols sampling methods, the physical constraints and the mass measurement capability of these sensors are investigated. Nano and micro sensors can be promising tools for aerosol mass concentration measurement systems, particularly in terms of sensitivity. A PM monitoring system can be achieved by combining an appropriate sampling method with nano or micro sensors. This review suggests different types of sensors that can be used as an appropriate option for PM monitoring, and suggests that fixed and reliable bulky systems are soon to be replaced by nano and micro scale sensors. Nevertheless, the latter systems should be further optimized in order to exhibit more accurate measurements.

1. Introduction

Over the past decades, PM exposure has been documented extensively because of its adverse health effects on human being. The toxicity of airborne particles depends on their size and their composition such as bulk chemical or trace element content, acid and sulfate content, etc. (Harrison & Yin, 2000). Indeed, particle size is of major importance. Particles which have diameters greater than 2.5 µm and less than 2.5 µm are usually referred as “coarse particles” and “fine particles” respectively. Thus, particles smaller than

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100 nm are referred as ''ultrafine particles'' or ''nanoparticles''. The fine and ultrafine particles can penetrate deeper in the human respiratory tract, and particle toxicity increases with high surface to volume ratio. It has been documented that the ultrafine particles trigger alveolar inflammation, and may lead to cardiovascular diseases and deaths (Seaton, MacNee, Donaldson, & Godden, 1995). Long-term exposures to $PM_{2.5}$ (Particle matter with aerodynamic diameter below 2.5 μm) were correlated with many types of cancers in the upper digestive tract, accessory digestive organs, lung in males and breast in females (Wong et al., 2016). In contrast, short-term exposures to $PM_{2.5}$ induce DNA hypo methylation which leads to activate inflammatory, vascular responses, and increase blood pressure (Bellavia et al., 2013). According to WHO (2016), the critical limit for yearlong and daylong exposure to $PM_{2.5}$ has been estimated at 10 μg/m^3 and 25 μg/m^3 respectively. Likewise for PM_{10}, the critical limits were at 20 μg/m^3 and 50 μg/m^3 respectively. Aerosol sampling consists in several fundamental methods such as filtration, inertial impaction, thermal precipitation, and electrostatic precipitation. Each of those methods can be adapted to an appropriate detection technique using optics or spectroscopy (e.g. Fluorescence, Raman) (Jonsson, Olofsson, & Tjärnhage, 2014), impedance (Carminati et al., 2014), radioactivity (Husar, 1974) or electromechanical mass measurements (Paprotny, Doering, Solomon, White, & Gundel, 2013). The latter can be applied to determine the mass-concentration of PM in ambient air.

As in microelectronics, the development of instrumentation for aerosol mass-concentration has followed the Moore's law: over the past decade, devices are getting smaller and smaller. Unlike traditional methods, Nano scale (devices that have nanoscale structures < 1 μm) or Micro scale (devices ranging from 1 to 100 μm) Electromechanical Systems referred as NEMS/MEMS have revolutionized the capacities for measuring the mass down to a single airborne particle. Sophisticatedly designed NEMS/MEMS allow the realization of integrable, inexpensive, portable, and low power consumption sensors. In recent years, the nano/microfabrication techniques have garnered considerable attention because they offer the possibility to build chip-scale real-time aerosols mass concentration measurement systems. Usually, a method for aerosol sampling is associated with a nano/micro sensor to assess the mass of particles. In this review, different types of mass measurement methods are presented. Particular attention is paid to the potential uses of systems of which mass concentration measurement can be achieved. An extensive literature review is proposed in order to examine the methods from past, present and future. Ultimately, the methodological tendencies for advanced real-time aerosol mass-concentration measurement are evaluated.

2. Materials and methods

2.1. First generation aerosol mass measurement methods: Bulky structures

Table 1 shows the best-known aerosols mass measurement systems and their related studies. Whereas these systems provide sufficient sensitivity for environmental monitoring, they remain expensive, labor intensive, time consuming, and bulky. In this article, we refer these types of methods as first generation mass measurement methods. At the present time, most of these methods are used for PM mass concentration measurements, PM classification and composition.

The first generation of mass measurement methods has been well-documented in the scientific literature. The methods have been classified in line with their ability to real-time monitoring mass measurement, an essential distinguishing feature for aerosols characterization (Amaral de Carvalho, Costa, & Pinheiro, 2015; Chow et al., 2002; Watson et al., 1998; Wilson et al., 2002).

The gravimetric method used for the mass measurement of PM_{10} and $PM_{2.5}$ has been described and validated as a reference method by the European Committee for Standardization (CEN). As shown in Table 1, this type of method is described in terms of flow rate and sensitivity. The measurement procedure consists in selecting particles by inertial separation at the inlet, followed by filtration and gravimetric analysis of collected particles on the filter. Despite this method is used as a standard method, it remains difficult to carry out accurate measurements because of a possible increase in particle-bound with water and the loss of semi-volatile compounds during the filtering process. As a result, the measured mass can be over/under estimated as compared with the real mass

Table 1
First generation aerosol mass concentration measurement systems: Bulky.

Particulate mass measurement methods	Sampling method	Flow rate	PM/Particle size separation	Real-time	Sensitivity	Ref.
Standard gravimetric measurement	Filtration	38.3 L/min	PM_{10}, $PM_{2.5}$ /No	No	1 μg/m^3 to 150 μg/m^3 for PM_{10}, 120 μg/m^3 for $PM_{2.5}$.	("CEN - European Committee for Standardization, ", 2014)
Beta Gauge	Filtration	–	PM_{10} / No	Yes	~3 μg/m^3	(Wedding & Weigand, 1993)
TEOM	Filtration	16.7 L/min	PM_{10} / No	Yes	~5 μg/m^3	(Ruppecht, Meyer, & Patashnick, 1992)
Berner Low Pressure Impactor	Impaction	30 L/min	60 nm to 10 μm/ Yes	No	–	(Wang & John, 1988)
QCM Cascade Impactor	Impaction	0.1 L/min	50 nm to 50 μm/ Yes	Yes	50–100 μg/m^3	(Chuan, 1976)
Electrical Low Pressure Impactor	Impaction	9.73 L/min	16.7 nm to 10 μm /Yes	Yes	–	(Yli-Ojanperä, 2010)
DMA-APM	–	0.53 L/min	PM_1/Yes	Yes	~10 μg/m^3	(Kihong Park, Kittelson, & McMurry, 2003)
Nephelometric	–	–	$PM_{2.5}$/No	Yes	12.95 μg/m^3	(Shendrikar & Steinmetz, 2003)