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Review article

Mobile monitoring of particulate matter: State of art and perspectives

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A B S T R A C T

Due to the socio-economic impact and the consequences on human health, the pollution associated to Particulate Matter (PM) represents one of the main emergences at a global scale. For these reasons, in the last decade we assisted to a continuously increasing interest in the mobile monitoring of PM on a regional and a local scale. Here we summarize the current status in this field, outlining the critical issues and the perspectives. The growing availability of instruments designed and optimized to the real-time monitoring of the air quality, considerably increased the spatial and temporal resolution of available datasets, actually improving air pollution maps and forecast models. However, several issues are still unresolved, particularly in terms of data representativeness. Indeed, the future PM monitoring devices have to be designed to support the decisional process but also the management of environmental emergencies in urban and industrial areas. The future of these devices is certainly the development of compact systems that will make possible a real-time characterization of size distribution, morphology, and chemical composition of the airborne particles.

Contents

1. Introduction

Particulate matter pollution has a considerable socio-economic impact due to its negative effects on human health and environment. Recently, the World Health Organization (WHO) estimated that exposure to tiny particles present in indoor and outdoor air pollution causes about 2 million death per year (WHO, 2011).

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Moreover, PM is one of the main cause of severe respiratory (e.g., asthma, emphysema, and lung cancer) and cardiovascular diseases (Aunan, 1996; Pope et al., 2009). Brook et al. (2010) highlighted the relation between $PM_{2.5}$ exposure and cardiovascular mortality and morbidity and stated that a reduction in PM levels may led to a decrease in cardiovascular disease within a few years. On the basis of remote sensing data, Van Donkelaar et al. (2010) suggested that 80% of the global population is exposed to $PM_{2.5}$ concentration higher than the limit values suggested by WHO AQG (i.e., 10 $\mu g/m^3$).

The health risks related to PM exposure are associated to the dimension and morpho-chemical features of the airborne particles (Fubini and Fenoglio, 2007 and references therein), in turn depending on the different emission sources/processes. In general, the smaller the particles, the greater the ability to reach the alveolus in the human lungs. Moreover, irregular particles (i.e., with high superficial area), have greater possibility to adsorb toxic and cancerogenous compounds. In this regard, the content in specific elements (e.g., content in soluble transition metals such as Fe, Ni, Cu, Zn, V) increases the adverse effects on human health.

In the last decades, we assisted to a massive migration of people toward large cities in all developing countries, a continuous urbanization process particularly important in Asia where China and India are the major players (Cohen, 2006). This process had a great impact on the air pollution on a global scale, a scenario that requires better and effective policies and, in addition improvements in the monitoring procedures and in the technique (Campbell-Lendrum and Corvalán, 2007). Moreover, indoor air pollution is one of the major public health concern, which increases the risk of chronic and acute respiratory disease and of acute infections (Bruce et al., 2000). Exposure to indoor air pollution is responsible for nearly 2 million excess deaths in developing countries (Bruce et al., 2000). In these countries, the principal source of indoor pollution is due to solid biomass used for domestic heating and cooking. Women and childrens are particularly exposed to air pollution induced risk (Bruce et al., 2000).

Although the most developed countries are achieving considerable success in reducing air pollution through focused strategies and the banning of high polluting industries (Smith, 2011; Tørseth et al., 2012), a significant proportion of Europeans still live in areas where regulated PM limits are constantly exceeded (EEA, 2014). A significant decrease of life expectancy has been observed (Raaschou-Nielsen et al., 2013; WHO, 2013).

During the last century, several air quality monitoring techniques were developed following the continuously improvements in air pollution knowledge, thus allowing the collection and the analysis of high quality data. Nowadays, airborne PM is constantly monitored by national environmental agencies through gravimetric measurements using high volume samplers (HVS). However, these devices are typically stationary, large, sparsely deployed and expensive (Fig. 1). Moreover, fixed stations are not sufficient to monitor adequately the air quality in large urban areas. Indeed, the concentration and chemical composition of PM in urban areas present considerable differences at a local scale depending on the emission sources, topography, and weather conditions (Monn et al.,

Fig. 1. Example of instruments currently used for PM monitoring. Standard devices: fixed monitoring station (left); high volume sampler (right). Professional devices, from left to right: Optical particle sizer (TSI 3330); optical particle counter (Kanomax 3900); scanning mobility particle sizer (TSI 3936); handheld optical particle counter (TSI Aerotrak 9303); nanoparticle surface monitor (TSI 3550). Low-cost sensors: Sharp GP2Y1010 sensor (left); SYhitech DSM501 sensor (right).

1997 and references therein). The limited number of available monitoring stations installed in the urban areas affects the resolution of air pollution maps/forecast models that are based on datasets generated by these devices (Jerrett et al., 2005; Hoek et al., 2008), which are also the only ones recognized by agencies and public institutions.

For the reason, mobile air quality monitoring is attracting an increasingly growing interest (Merbitz et al., 2012; Patton et al., 2014; Van den Bossche et al., 2015). Several devices were developed to monitor in real-time the spatial and temporal variability of air quality using different instruments, technologies, and platforms. At present, mobile devices can be used to monitor with high spatial resolution the different classified components of PM, e.g., PM_{10}, $PM_{2.5}$, ultrafine particles (UFPs), PM_1, black carbon (BC) and the Total Suspended Particles (TSP).

In this contribution, we will summarize the status of PM mobile monitoring, describing the main instruments and the currently used platforms. Finally, we will discuss the critical issues and the perspectives in this field.

2. The status of mobile PM monitoring

With the advent of portable instruments providing high-time resolution and real-time data, the approach to air quality monitoring has deeply changed. A wide typology of professional and accurate instruments is now available for real-time measuring of several properties of airborne particles. The number of particles is efficiently measured using optical particle counters (OPC; Kulkarni et al., 2011) and condensation particle counters (CPC; Cheng, 2011). OPC and CPC are based on the detection of light scattered when a particle passes through a beam of light; the difference between these two instruments is the minimum particles dimension that can be detected, i.e., 50 nm for OPC and 2 nm for CPC. The distribution of the aerodynamic size of particles can be measured through scanning mobility particle sizers (SMPS; Sioutas, 1999), aerodynamic particle sizers (APS; Sioutas, 1999), optical particle sizers (OPS; Chazette et al., 2005), and differential mobility particle sizers (DMPS; Keady et al., 1983). The particle mass concentration can be monitored by tapered element oscillating microbalance (TEOM; Patashnick and Rupprecht, 1991), beta attenuation mass monitor (BAM; Gobeli et al., 2008), continuous aerosol mass monitor (CAMM; Hopke, 2003) and nephelometer (Brauer et al., 1995). The active surface area of the nanoparticles can be measured through a nanoparticle surface area monitor (NSAM; Shin et al., 2007). Moreover, dedicated instruments may provide the concentration of selected components of PM, e.g., black carbon (BC), and ultrafine particles (UFP; particles less than 100 nm). The BC mass loading can be measured by both multiangle absorption photometer (MAAP; Slowik et al., 2007) and particulate soot absorption photometer (PSAP; Slowik et al., 2007). The number concentration of UFC is measured by ultrafine particle counters (UPC; Brock et al., 2000).

These professional instruments have been used on different platforms (i.e., car, van, pedestrian, bicycle, tram, airship) for mobile monitoring of the various properties of PM. In particular, mobile air quality monitoring is mainly carried out through motor vehicles that can be equipped with voluminous and moderately heavy instruments (e.g., Kolb et al., 2004; Westerdahl et al., 2005; Wang et al., 2009; Padró-Martínez et al., 2012; Levy et al., 2014). During the 2008 Beijing Olympic Games, Wang et al. (2009) equipped a van with a large suite of devices for measuring particles size distribution, nanoparticle active surface area, and black carbon concentration (Table 1). More compact and light-weight devices can be transported by pedestrians (e.g., Kaur et al., 2007; Zwack et al., 2011; Hsu et al., 2014). Zwack et al. (2011) reports data of volunteers equipped with backpacks containing instruments to measure ultrafine particle and $PM_{2.5}$ concentrations within New York street canyons (Table 1). Another really portable system for cooperative monitoring of air quality (MONICA) was developed by ENEA (the Italian national agency for research on alternative energy, patent RM2014C06806). The system has been used to promote the participatory approach to air quality, sharing information in polluted urban areas through social platforms. Bicycles (e.g., Elen et al., 2013; Peters et al., 2014; Sullivan and Pryor, 2014) have been obviously considered for air quality mapping and exposure assessment in urban environments. Elen et al. (2013) equipped a bicycle with a set of measurement devices for monitoring UFP, PM_1, $PM_{2.5}$, PM_{10}, TSP and BC concentration using an automated data

Table 1
Summary table of the main articles on mobile monitoring of PM reporting information on the instrumentation, platform, and measured parameters.

Author-funding institution	Platform	Instrumentations	Measured parameters	Objectives	References
Wang et al. (2009) – Beijing Environmental Protection Bureau	Van	Scanning mobility particle sizer-TSI DMA3081, Optical particle counter – Grimm Dust monitor 1.108 Nanoparticle Surface Area Monitor/TSI 3550 Multiangle Absorption photometer-Thermo Model 5012	Size distribution D = 15 –673 nm Size distribution D = 0.3 –20 μm Active surface area Black carbon Position	Verify the effectiveness of pollution control policies adopted for the 2008 Beijing Olympic Games.	Levy et al., 2014; Padro-Martinez et al., 2012; Westerdahl et al., 2005; Kolb et al., 2004
Zwack et al. (2011) – Gilbert and Ildiko Butler Foundation and Toxicology	Pedestrians	TSI, P-Track 8525 TSI, DustTrack 820	Ultrafine particles (UFP) $PM_{2.5}$	Discern contributions of traffic within street canyons by regression techniques	Hsu et al., 2014; Kaur et al., 2007
Elen et al. (2013) – Flemish Agency for Innovation by Science and Technology	Bicycle	TSI, P-Track 8525 GRIMM 1.108 dust monitor AE51, AethLabs microAeth	Ultrafine particles (UFP) PM_1, $PM_{2.5}$, PM_{10}, TSP Black Carbon (BC)	mobile air quality monitoring in small areas	Sullivan and Pryor, 2014; Peters et al., 2014
Castellini et al. (2014) – ARPA Umbria	Cabin of urban metro system	Customized optical particle counter (OPC)	Size distribution (0.28 –10 μm)	Monitoring air quality in urban environment	Hasenfratz et al., 2014
Frick and Hoppel (2000) – US Navy	Airship	NRL DMA size spectrometer PMS optical particle counter TSI condensation particle counter	Size distribution (0.005 –0.6 μm) Size distribution (0.25 –23.5 μm) Size distribution (>0.003 μm)	Effect of ship's exhaust on marine boundary layer	Plant et al., 1998 Frick and Hoppel, 1993

transmission system (Table 1). In urban areas, the public transportation systems (e.g., tram, underground) represents a powerful platform for housing mobile air quality devices (e.g., Castellini et al., 2013, 2014; Hasenfratz et al., 2014). Castellini et al. (2014) performed measurements of particles concentration through an aerosol monitoring system (PMetro) based on a customized optical particle counter integrated on a cabin of the metro transport system in Perugia (Italy) (Table 1). Also airships can be really effective for PM monitoring, although above the ground level (e.g., Frick and Hoppel, 1993, 2000; Plant et al., 1998). As an example, Frick and Hoppel (1993, 2000) utilized airships to assess the effect of ship's exhaust plume on the marine boundary layer through measurements of the particles size distribution (Table 1).

The applications of low-cost sensors to PM monitoring is continuously increasing (Dutta and Culler, 2009; Hasenfratz et al., 2012; Budde et al., 2014). Although their accuracy is not comparable with professional instruments, the main advantages are the small dimension and the low power demand. Moreover, the low cost allows also a large-scale distribution and application in handheld devices (Budde et al., 2014). If necessary, the low accuracy of such sensors can be improved by appropriate calibration techniques (Budde et al., 2012). As an example, Budde et al. (2013a) demonstrated that a dust sensor (Sharp GP2Y1010; Fig. 1) may be effectively employed for PM monitoring after a proper calibration. Khadem and Sgarciu (2014) proposed the integration of the same sensor within a network to collect dust concentrations in industrial sites. The data comparison with professional air quality monitoring devices showed very promising results. Li et al. (2014) developed another cost-effective portable device, the PiMi air box, always based on a low-cost sensor (i.e., SYhitech DSM501; Fig. 1). After the calibration, data provided by the PiMi air box correspond reasonably well with the data collected at fixed stations with real-time professional devices and released by governmental institutions. Weekly et al. (2013) also demonstrated that the SYhitech DSM501 sensor, if properly calibrated, satisfactorily measured the concentration of particles > 2.5 μm also in indoor. They also described the necessary hardware developments for the real-time availability of data using the wireless technology.

The development of smartphone-based systems is indeed another promising way of monitoring PM with handheld devices. The ubiquity of smartphones and their networking capabilities may allow air quality monitoring and the immediate availability on public media. Recently, Ramanathan et al. (2011) described the application of a smartphone-based technology for real-time monitoring of BC concentrations based on the analysis of photographs captured by the phone camera and transmitted on-line. Budde et al. (2013b) also retrofitted a cellphone camera with a low cost sensor, using camera and flash as receptor and light source, respectively. Snik et al. (2014) developed iSPEX, another low-cost optical device, using the smartphone camera applet. The software transforms the phone into a spectropolarimetric instrument that allows aerosol optical thickness (AOT) measurements. Although the single measurement is of relatively low quality, the combination of measurements provided by thousands devices may allow AOT mapping of large areas that are in good agreement with those provided by remote sensing imagery and by more accurate ground-based photometric stations.

3. Critical issues and perspectives on PM mobile monitoring

The main question, which arises when discussing about PM monitoring, regards the balance between pros and cons of the use of many compact and low-cost instruments vs. a limited number of more expensive and accurate professional devices. Actually, many low-cost sensors are easy-to-use, have small dimension and require limited power to operate continuously. They may provide to individuals the opportunity to monitor the local air quality. The low-cost makes them also suitable for large scale applications and the construction and exploitation of high-resolution maps obtained from a large number of single measurements. The drawbacks of low-cost sensors lie in their high noise, low stability, and limited accuracy although the latter can be improved by an appropriate calibration and an optimized data processing. Moreover, these sensors allow only to measure the total suspended particles (TSP) (Budde et al., 2014). On the contrary, many professional devices are extremely accurate, allow monitoring of various properties of airborne particles (see the previous paragraph) and have been optimized for mobile monitoring. Some are certified by the governmental environmental agencies for official air quality measurements. However, at present, their high cost makes them unsuitable for large-scale investigations and for pollution imaging.

Another critical issue related to PM mobile monitoring arises from the high temporal and spatial variation in PM concentrations in urban areas. To derive time-representative pollutants maps associated to different traffic and meteorological conditions a large amount of data are required (Padró-Martínez et al., 2012; Van de Bossche et al., 2015). The need for a high number of repeated measurements to assess the temporal and spatial variability of air pollutants has been recently raised by Peters et al. (2014). However, the minimum number of measurements to get a reliable representation of the variability of pollutants is not straightforward (Van Poppel et al., 2013). Essentially, the number of repeated measurements is a function of the desired spatial resolution (Van de Bossche et al., 2015). An appropriate background correction of the final must be also considered (Van de Bossche et al., 2015).

The chemical characterization of PM is another crucial issue and is mandatory to identify the origin of specific components, i.e., their emission sources. Currently, the chemical features of airborne particles are determined with different analytical techniques able to perform major and trace elemental analysis, and anion and cation speciation analysis, e.g., XRF, ICP-MS, PIXE, INAA, AAS, IC, AC. Although instruments allowing real-time measurements of the chemical composition of PM have been developed and are currently available (e.g., ion trap mass spectrometer, aerosol chemical speciation monitor, thermal desorption chemical ionization mass spectrometry), at present they still cannot be easily extended to mobile platforms mainly due to their dimensions (e.g., Yang et al., 1996; Voisin et al., 2003; Held et al., 2009; Smith et al., 2014; Petit et al., 2015; Ripoll et al., 2015). Additional limitations for the integration of these instruments is the low concentrations of some chemical components in PM that would require long acquisition times. As an example, Voisin et al. (2003) reported the application of thermal desorption chemical ionization mass spectrometry to the analysis of ammonium sulfate nanoparticles with a sensitivity to ambient mass concentration of 50 pg/m^3 using an aerosol sampling flow of 8 L/min and a collection time of 10 min.

A major demand in PM mobile monitoring is the development of compact (i.e., suitable for different mobile platforms) and high performance instruments for real-time chemical analysis. Still a critical issue is the sensitivity to aerosol mass concentration. Currently, the real-time chemical characterization of aerosol allows a time resolution of tens of minutes and a maximum sensitivity to aerosol concentration of tens of pg/m^3 (Voisin et al., 2003; Crippa et al., 2013).

Actually, taking in consideration the major demands, an ideal instrument for air quality monitoring should be able to characterize

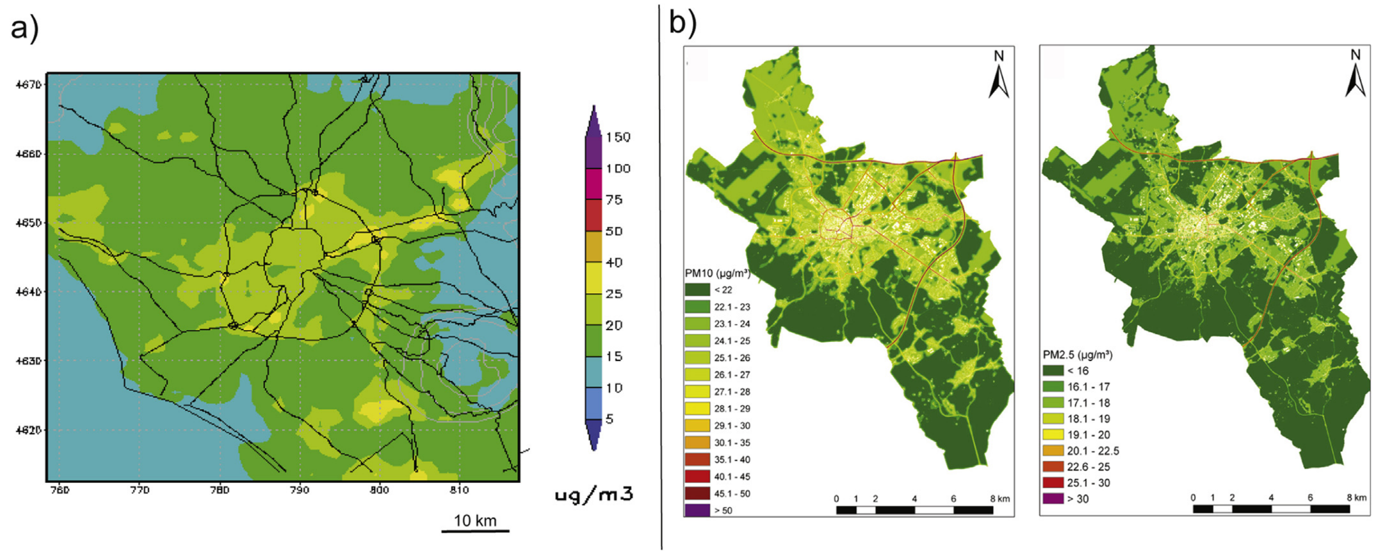

Fig. 2. a) Forecast map of the PM_{10} concentration in the city of Rome (Italy) obtained on the basis of PM_{10} measurements at 23 fixed stations (source: ARPA Lazio); b) modeled maps of the PM_{10} and $PM_{2.5}$ concentrations in the city of Aachen (Germany) obtained by mobile measurements at 40 sites (after Merbitz et al., 2012). To be noted the remarkably higher spatial resolution of the map based on mobile measurements.

the number of particles along with their size, chemical composition and morphology (Friedlander, 1971; Flagan, 1993). Although considerable progresses have been achieved in the last years, many desired performances are still far to be satisfied by any existing device. All in all the next generation of mobile air quality devices for PM mobile monitoring will have to answer to the following issues related:

3.1. Spatial and temporal resolution in urban environments

The air quality of urban environments are characterized by high spatial and temporal variability (e.g., Briggs et al., 2000; MacNaughton et al., 2014), which not always exhibits a clear periodicity (Song Guo et al., 2014). The PM variability coupled with the limited data collected by fixed monitoring stations (Briggs et al., 2000), affects the reliability of the available pollution maps and does not adequately support the development of air quality models. The employment of flexible, low-cost devices, compatible with different means of transports may allow to set-up a wider and flexible air monitoring network. This approach may certainly increase the spatial and temporal resolution of air quality models and maps (Fig. 2).

3.2. Background pollution level

Small dimension, easily transportable devices can be used to monitor pollution level at remote sites, e.g., rural and mountain areas, where the number of fixed stations is forcedly low due to problems related to accessibility and limited availability of power supply. There is a significant scarcity of data in this issue, causing discrepancies between forecast models and measurements in polluted areas (Basagaña et al., 2012). Improved and more accurate spatial and time monitoring in remote areas is thus mandatory to improve air circulation and climate models both on regional and global scale.

3.3. Morphological and chemical characterization of airborne particles

As we have outlined above, the reason for the toxicity of airborne particles lies mostly in their morphological and chemical features. Therefore, the morpho-chemical characterization of aerosol particles, e.g., elemental associations, surface coatings, compositional variation with particle size, trace elements content, is crucial for evaluating the potential health risks. It is then essential to develop instruments that can return morphological and chemical information of airborne particles in near real-time, and compatible with a high spatial resolution (e.g., tens of meters) of the chemical features of PM. Moreover, the real-time morpho-chemical characterization of PM through mobile device can allow discriminating the various sources of pollutants, e.g., power plants, steel plants, waste incinerators, etc., as well as to recognize external contributions and pathways of pollutants (Lahd Geagea et al., 2008; Grobety et al., 2010). Such information are crucial for the effectiveness of air pollution control policies allowing the implementation of specific actions focused on the main pollutants or to the recognition of the most dangerous sources of pollutants.

Because of the reasonably low cost, these devices could be also used for.

3.4. The evaluation of a monitoring site

Prior to establishing a fixed monitoring station for PM monitoring in a defined area, it is better to identify a representative site, and to assess its suitability;

3.5. Air pollution monitoring in emerging and developing countries

In countries with limited financial resources, cost-effectively alternatives for air quality monitoring to fixed stations have to be considered. In addition, in all developing countries, where the industrialization and urbanization are increasing at a fast rate, air pollution issues are dramatically increasing (Klimont et al., 2001). Low-cost and high-accuracy mobile devices may be used to setup in a short time affordable air quality monitoring networks;

3.6. Monitoring of short-lived events

Unpredictable and sudden natural events (e.g., forest fires, volcanic eruptions, dust storms) constitute potential hazards for large areas. In this framework, it is necessary to be ready to monitor air quality with high resolution to respond to the localized character of these emergences.

4. Concluding remarks

Air pollution and environmental protection are certainly among the most important issue of public concern everywhere in the world. For this reason, in the last decade, mobile monitoring has acquired a significant relevance for monitoring air quality at high spatial resolution. Nowadays, a large spectrum of instruments is available for real-time monitoring of PM, from professional devices to low-cost sensors. Both have advantages and drawbacks and the choice is determined by the goal of the monitoring campaign but also on the available budget. Professional instruments are accurate, suitable to monitor various properties of PM, and can be also used for mobile monitoring. On the contrary, they cannot be used in large monitoring networks mainly because of their high cost. At present, low-cost sensors can monitor a limited number of PM features, but are particularly suitable for participatory monitoring. Indeed, it has been already demonstrated that their limited accuracy can be increased with an appropriate calibration and an optimized data process (Budde et al., 2013a). In the next years advancements are expected associated to the development of instruments capable to perform real-time chemical characterization of aerosol particles, with a higher sensitivity and size matching the compact dimensions of mobile platforms. Capabilities to perform real-time analysis of the diverse morpho-chemical features of airborne particles (i.e., size distribution, morphology, chemical composition) will be the fundamental requisite of the next generation of mobile monitoring devices.

Conflict of interest

The authors certify that they have NO affiliations with or involvement in any organization or entity with any financial/non-financial interest in the subject matter or materials discussed in this manuscript.

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