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Airborne ultrafine particles in a naturally ventilated metro station: Dominant sources and mixing state determined by particle size distribution and volatility measurements☆

Luís Mendes [a, b], Maria I. Gini [a], George Biskos [c, d], Ian Colbeck [e], Konstantinos Eleftheriadis [a, *]

[a] Institute of Nuclear & Radiological Sciences & Technology, Energy & Safety — Environmental Radioactivity Laboratory, N.C.S.R. "Demokritos", Aghia Paraskevi, 15310 Athens, Greece
[b] University of the Aegean, Department of Environment, 81100 Mytilene, Greece
[c] Faculty of Civil Engineering and Geosciences, Delft University of Technology, 2628 CN Delft, The Netherlands
[d] Energy, Environment and Water Research Center, The Cyprus Institute, 2121 Nicosia, Cyprus
[e] School of Biological Sciences, University of Essex, Colchester CO4 3SQ, UK

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ABSTRACT

Ultrafine particle number concentrations and size distributions were measured on the platform of a metro station in Athens, Greece, and compared with those recorded at an urban background station. The volatility of the sampled particles was measured in parallel, providing further insights on the mixing state and composition of the sampled particles. Particle concentration exhibited a mean value of 1.2×10^4 # cm^{-3} and showed a weak correlation with train passage frequency, but exhibited a strong correlation with urban background particle concentrations. The size distribution appears to be strongly influenced by outdoor conditions, such as the morning traffic rush hour and new particle formation events observed at noon. The aerosol in the metro was externally mixed throughout the day, with particle populations being identified (1) as fully refractory particles being more dominant during the morning traffic rush hours, (2) as core-shell structure particles having a non-volatile core coated with volatile material, and (3) fully volatile particles. The evolution of particle volatility and size throughout the day provide additional support that most nanoparticles in the metro station originate from outdoor urban air.

1. Introduction

Airborne nanoparticles (i.e. particles having diameter <50 nm) and ultrafine particles (UFP, i.e. particles having diameter <100 nm) have been shown to cause adverse health effects (Donaldson et al., 2002; Knol et al., 2009; Nel et al., 2006; Oberdörster et al., 2005), and are therefore important to monitor their concentrations in the breathing air. Epidemiological and toxicological studies have shown that nanoparticles may be more harmful than larger particles due to their high surface area to mass ratio, and their ability to reach and deposit in the alveolar region where they can interact with epithelial cells (Brown et al., 2002). In addition, translocation of inhaled nanoparticles to the brain via the olfactory nerve system can cause oxidative stress and induce DNA damage (Bräuner et al., 2007; Maher et al., 2016; Möller et al., 2005).

Commuting in polluted urban areas increases the daily human exposure to UFP, thereby enhancing the possibility of causing health problems (Knibbs et al., 2011). Metro systems are widespread around the world, providing unquestionable advantages as an environmentally-friendly and energy-efficient means of transport that relieves surface traffic. Being mostly a confined underground environment, concerns have been raised for the air quality within metro stations and the paths connecting them with the outdoor environment. Particulate matter (PM) in the metro has been investigated by several studies worldwide (Abbasi et al., 2013; Martins et al., 2016a, 2016b, 2015). Most of these studies focused on coarse and fine particles (i.e. PM_{10} and $PM_{2.5}$), showing that the concentration levels are consistently higher in the underground environment compared to those observed in the outdoor ambient

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* Corresponding author.
E-mail address: elefther@ipta.demokritos.gr (K. Eleftheriadis).

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air. Studies conducted at Beijing and Shanghai have also shown that indoor sources can alter both particle mass and size of the airborne particles in subway systems (Cui et al., 2016; Zhang et al., 2011). Despite the importance of particles having sizes in the submicron and the nanometer range for determining air quality, few studies have reported on their concentration in metro stations. Doing so is particularly important given that the number concentration of airborne nanoparticles can reach extremely high levels without this being picked up by the PM_{10} and/or the $PM_{2.5}$ mass concentration measurements (Morawska et al., 2008).

Measurements of aerosol nanoparticles in the metro environment have been undertaken in Boston (Levy et al., 2002), London (Seaton et al., 2005), Helsinki (Aarnio et al., 2005), Taipei (Cheng et al., 2009), Stockholm (Gustafsson et al., 2012; Klepczyńska Nyström et al., 2010; Midander et al., 2012), Prague (Cusack et al., 2015), Barcelona (Moreno et al., 2015b; Reche et al., 2017) and Rome (Grana et al., 2017). Based on total particle number concentration measurements, most of these studies have suggested that the dominant UFP source is outdoor air. Reche (et al., 2017) observed low correlation between indoor particle number and metro sources for the UFP size range. Although mechanical processes usually generated fine and coarse particles, emission of nanoparticles have been reported from several metro sources, including wheel-rail interfaces and brake pads (Abbasi et al., 2011; Namgung et al., 2016; Sundh et al., 2009), sparking from the power supply contacts (Meuller et al., 2012) and contact-shoe interface with third-rail (Cha et al., 2016). Identification of sources and exposure of commuters to nanoparticles would be better determined if, in addition to the concentration, the size distribution and composition of the particles is measured in near real time. Online measurements of the size distribution of airborne UFP can be achieved by electrical mobility methods (Wang and Flagan, 1990).

Determining the chemical composition of UFPs, is challenging as the chemical composition of the PM_{10} or PM_1 mass fraction cannot provide useful conclusions for a fraction of this population of particles, of which the UFPs constitute the 10^{-6} or 10^{-3} part of this mass. Therefore, the number size distribution of this fraction alone, separated from the bulk of the mass of higher sizes, their volatility and changes in the size distribution of the UFP fraction provides meaningful information and indirect evidence of their chemical nature (volatile or refractory type of species). Rizza et al. (2017) have recently found that a lower variability of PM_{10} concentrations was detected with respect to number and alveolar-deposited surface area concentrations. These phenomena can be ascribed to the predominant contribution of ultrafine particles to both number and alveolar-deposited surface area metrics. Probing particles volatility (An et al., 2007; Burtscher et al., 2001; Giamarelou et al., 2016; Jennings et al., 1994; Kittelson et al., 2002; Kuhn et al., 2005; Orsini et al., 1999; Philippin et al., 2004; Poulain et al., 2014; Sakurai et al., 2003) in near real time using Tandem Differential Mobility Analyzer (TDMA) systems provides a great method for determining indirectly their composition (Bezantakos et al., 2013; Giamarelou et al., 2016). In addition, the method can provide information on morphology (Biskos et al., 2006) and mixing state (Bezantakos et al., 2013) thereby being a valuable addition to the size distribution and concentration measurements. In view of that, applying this technique to the metro environment here for the first time makes the measurements novel and unique.

This study aims to characterize ultrafine and nanoparticles in a station of the Athens metro system using measurements of particle number concentrations, size distributions and volatility. Particle concentration and size distribution measurements were performed in the metro station and compared with those measured outdoors. Volatility measurements were used as a means to characterize the composition of the particles and determine their mixing state. The indoor or outdoor origin of the particles was also investigated using the daily patterns of size distribution and concentration levels.

Comparing with PM_{10} and $PM_{2.5}$ mass fractions, a limited number of studies have focused on UFP in metro systems, and this is the first study to combine detailed size resolved concentration of UFP with particle volatility measurements, providing further insights into their mixing state and origin.

2. Material and methods

2.1. Measurement site and instruments

The metro of Athens consists of 3 lines and 65 stations, and carries around 1.35 million passengers daily, resulting in an estimated reduction of 71×10^3 private vehicles in the city. The measurements took place on the platform of the Nomismatokopio metro station, which is part of Line 3 (Blue line) of the Athens metro, and lasted for three weeks: i.e., from 28 April to 19 May 2014. This is the longest continuous measurement period of ultrafine particles size distribution in a metro station to date. It was considered adequate to assess general daily variability in the aerosol properties, considering that the conditions inside the metro follow a cycle of 24 h, and this is also the case to some extent for the outdoor concentration in urban areas affected by traffic (Dall'Osto et al., 2011; Ma and Birmili, 2015; Shi et al., 1999). The internal conditions of the metro are relatively stable along the year, especially since ventilation settings and train frequency are kept unchanged.

The station studied is representative of the underground stations (lines 2 and 3) of the metro of Athens, sharing the design and ventilation settings with the vast majority of the other stations (Fig. 1). The features of the station regarding the surrounding area are typical of the Athens Metro stations, which are mostly located along a busy traffic avenue, and in that respect the station is representative of most Athens and most large metropolitan areas metro stations.

The metro station is located in the northeast suburbs of Athens, in a residential area and underneath one of the main avenues (i.e., Mesogeion Avenue) of the city, characterized by heavy traffic, especially during rush hours (cf Fig. S1 of supplementary information). This station is one of the deepest in Athens, at 20 m below the surface. The station shares the architectural design of most stations in the metro of Athens, and it is composed of three levels below the surface: the first where the two main passenger's pathways to the outdoor are located, leading to both sides of the Mesogeion Avenue; the second level that includes the tickets office; and finally, the third level where the waiting platforms and railway are located. There is a single tunnel with two side-by-side rail tracks, and one waiting platform in each side of the railway. It should be noted here that none of the stations of the Athens Metro system are equipped with screen doors isolating the platforms from the tunnels, and thus the air at the stations is strongly influenced by the passing trains. There are two ventilation shafts from the tunnels to outdoors, located immediately before and after the platforms. This set-up is optimal for naturally ventilated stations (Jia et al., 2009; Kim and Kim, 2009). The power supply to the trains is based on a third-rail system, in which the trains are attached with contact-shoes. The station is equipped with forced ventilation systems, but these are used only for temperature control or emergency actions (e.g. exhaust of fire fumes), which was not necessary during the campaign. The only active ventilation on the platform level is through air slits on the sides of the rail area which aim to cool the engines and the braking system of the trains. Natural ventilation is the main mechanism for air exchange with the outdoor environment through wide ventilation shafts and the