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Vertical profiles of lung deposited surface area concentration of particulate matter measured with a drone in a street canyon☆

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ABSTRACT

The vertical profiles of lung deposited surface area (LDSA) concentration were measured in an urban street canyon in Helsinki, Finland, by using an unmanned aerial system (UAS) as a moving measurement platform. The street canyon can be classified as an avenue canyon with an aspect ratio of 0.45 and the UAS was a multirotor drone especially modified for emission measurements. In the experiments of this study, the drone was equipped with a small diffusion charge sensor capable of measuring the alveolar LDSA concentration of particles. The drone measurements were conducted during two days on the same spatial location at the kerbside of the street canyon by flying vertically from the ground level up to an altitude of 50 m clearly above the rooftop level (19 m) of the nearest buildings. The drone data were supported by simultaneous measurements and by a two-week period of measurements at nearby locations with various instruments. The results showed that the averaged LDSA concentrations decreased approximately from 60 $\mu m^2/cm^3$ measured close to the ground level to 36–40 $\mu m^2/cm^3$ measured close to the rooftop level of the street canyon, and further to 16–26 $\mu m^2/cm^3$ measured at 50 m. The high-resolution measurement data enabled an accurate analysis of the functional form of vertical profiles both in the street canyon and above the rooftop level. In both of these regions, exponential fits were used and the parameters obtained from the fits were thoroughly compared to the values found in literature. The results of this study indicated that the role of turbulent mixing caused by traffic was emphasized compared to the street canyon vortex as a driving force of the dispersion. In addition, the vertical profiles above the rooftop level showed a similar exponential decay compared to the profiles measured inside the street canyon.

1. Introduction

Street canyons are important microenvironments in urban areas with respect to the dispersion of traffic emissions and human exposure. Pedestrians, cyclists, and people inside vehicles may be exposed to relatively high concentrations of particles and gaseous pollutants on the ground level of street canyons because of the reduced natural ventilation (Kumar et al., 2011; Vardoulakis et al., 2003). Vertical dispersion of pollutants affects the human exposure in buildings above the ground level and contributes to regional background concentrations as well as to the global atmospheric effects of anthropogenic emissions. According to Monks et al. (2009), the characterization of the vertical profiles in urban areas and street canyons is crucial in determining pollution transport from the urban area to the regional scale. Understanding of the vertical dispersion in street canyons also provides a possibility of improvements in urban planning, building ventilation, and indoor air quality (Ai and Mak, 2015).

The fine particulate matter, i.e. the particles with a diameter smaller than 2.5 μm (PM2.5), has been estimated to cause about 3.3 million premature deaths per year worldwide (Lelieveld et al., 2015). The problem is emphasized nowadays in Asia but also, in spite of the strict emission and air quality standards, still

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recognized in Western countries (Beelen et al., 2014). The mass of fine particles has been widely monitored in urban areas all over the world (Cheng et al., 2016) and shown to correlate with the incidence of cardiopulmonary diseases (Silva et al., 2013). In addition to the negative health effects, aerosols emitted from anthropogenic sources have also an impact on global climate (Rotstayn et al., 2009). In order to better understand the urban air quality with respect to the particulate matter and the effects of anthropogenic sources on global climate, a lot of different measurements conducted in urban environments have been reported, including particle number concentrations and number size distributions (Shi et al., 1999; Pant and Harrison, 2013; Pirjola et al., 2012), as well as chemical composition of particles (Putaud et al., 2004; Pirjola et al., 2017).

Recently, an increasing number of studies have reported surface area related quantities measured in urban areas. The reason for this trend can be found in toxicological studies where the surface area of particles has been shown to correlate with negative health effects better than the mass and number concentrations (Brown et al., 2001; Oberdörster et al., 2005). One of the most common surface related metric is the lung deposited surface area (LDSA) concentration that can be defined separately for the alveolar or trancheobronchial regions of lungs. The alveolar LDSA concentration has been found to be on average between 10 and 89 $\mu m^2/cm^3$ at urban background measurement stations located in different Western cities (Reche et al., 2015). According to a recent study by Kuuluvainen et al. (2016), traffic related particle modes dominate the size distribution of the LDSA and the average concentrations are usually at the highest at busy traffic sites.

The interest towards street canyons as significant microenvironments in urban areas has resulted in various measurements and development of models. It is commonly known that the highest concentrations of fine particles in urban areas usually exist in closed street canyons with relatively high and long buildings parallel to the street (Kumar et al., 2011; Pirjola et al., 2012). The basic dispersion of aerosol particles and other pollutants in a street canyon is characterized by the vortex caused by the predominant wind above the building rooftop level and the turbulent mixing affected by bypassing vehicles (Qin and Kot, 1993). Kumar et al. (2009b) compared the performance of three different street canyon models including an operational street pollution model (OSPM) (Berkowicz, 2000), a semi-empirical box model, and a computational fluid dynamics (CFD) model. They found that the OSPM and box-based models were able to predict the similar shape of concentration profiles corresponding to pseudo-simultaneously measured values reported by Kumar et al. (2008b). Both of these models include calibration parameters based on experimental data from various field studies. The vertical profile of pollutant concentrations in a street canyon have also shown to follow an exponential form by multiple other studies. In a theoretical study (Huang, 1979), two wind tunnel experiments (Hoydysh and Dabberdt, 1988; Dabberdt and Hoydysh, 1991), and four field measurements studies (Capannelli et al., 1977; Zoumakis, 1995; Chan and Kwok, 2000; Vardoulakis et al., 2002), the concentrations were found to be the highest near the canyon bottom with a decreasing gradient towards the rooftop level.

A lack of experimental data or uncertainties related to the available data often restrict the evaluation of street canyon models. Several studies have reported particle concentrations and other pollutants measured at the ground and rooftop level of street canyons (Väkevä et al., 1999; Kukkonen et al., 2001; Pakkanen et al., 2003; Kumar et al., 2009a). The decrease of concentrations with the increasing altitude has been evident. Marini et al. (2015) conducted a measurement campaign with simultaneous aerosol particle measurements at three or four different heights on both sides of a symmetric street canyon and pointed out the strong influence of wind conditions on the particle concentrations in the canyon. It is noteworthy that unlike inert gases, such as carbon dioxide (CO_2), aerosols consist of particles of different sizes and composition, which may behave differently and interact with each other during dispersion and dilution processes (Kumar et al., 2008b; Imhof et al., 2005). Some measurements of carbon dioxide have been conducted at different heights up to 30 m in a lattice tower located in a street canyon with a rooftop level at the height of 15 m (Vogt et al., 2006). However, these results cannot directly be applied for particulate matter because of the inert nature of carbon dioxide and its relatively high and variable background levels compared to the ambient values in urban environments.

In general, the vertical concentration profiles of particulate matter and other pollutants can be measured with stationary or moving measurement platforms installed onto the walls of buildings and other constructions, or with flying measurement platforms. The above-mentioned studies reporting particle and CO_2 concentrations in street canyons are examples of stationary measurements. On the other hand, Imhof et al. (2005) measured particle concentrations and size distributions by using an elevator installed into a tower as a moving measurement platform at an open motorway environment. Recently, the development of unmanned aerial systems (UAS) or unmanned aerial vehicles (UAV), commonly known as drones, has enabled the measurement of vertical profiles especially by using sensor-type instruments with a light weight and a high time resolution. Villa et al. (2016) reviewed the use of drones in the air quality research and they found that the field is in its early stages of development. Most of the studies reporting measurements with a drone are focused on meteorological parameters, such as temperature and relative humidity, and they have been performed by using fixed-wing drones that are not applicable for measuring vertical profiles close to the ground level (Elston et al., 2015). Only a few studies have reported measurements of particulate matter with a drone. Brady et al. (2016) demonstrated the performance of a rotary-wing drone equipped with an optical particle counter and a CO_2 sensor for vertical gradient measurements at the surf zone of an ocean. In a recent study by Villa et al. (2017), the vertical profiles of particle number concentration were measured with a drone adjacent to a motorway by using a sensor, based on the diffusion charging of particles.

The aim of this study was to investigate the vertical profiles of lung deposited surface area concentration in an urban street canyon. Measurements were performed with a miniature electrical particle sensor installed into a multirotor drone that was operated from the ground level to an altitude clearly above the rooftop level of the street canyon. The obtained vertical profiles were supported by stationary measurements at different heights and ground level measurements at nearby locations. The experimental data were analyzed further by using exponential fits and parametrization, the aim of which was to compare the results to previous studies. Altogether, this study demonstrates the performance of a drone in an urban street canyon environment for measurements of fine particles.

2. Methods

Measurements were carried out in a busy street canyon in Helsinki, Finland, next to an urban supersite air quality measurement station (Mäkelankatu 50; 60°11′N, 24°57′E) operated by the Helsinki Region Environmental Services Authority (HSY). The location of the measurement station is shown on the map in Fig. 1a and b. The supersite measurement station consists of a container (length 8.0 m, width 1.7 m, height 2.7 m) that is equipped with the standard air quality measurement devices and other