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Characterization of indoor aerosol temporal variations for the real-time management of indoor air quality

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HIGHLIGHTS

- Temporal variation of indoor PM has been quantitatively characterized.
- Database for dynamic control of IAQ based on PM sensors has been created.
- Removal of UFPs from indoor air by ventilation is complicated.
- Centre of ceiling and exhaust ventilation serve as adequate sites for PM sensors.

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ABSTRACT

The study presents the characterization of dynamic patterns of indoor particulate matter (PM) during various pollution episodes for real-time IAQ management. The variation of PM concentrations was assessed for 20 indoor activities, including cooking related sources, other thermal sources, personal care and household products. The pollution episodes were modelled in full-scale test chamber representing a standard usual living room with the forced ventilation of 0.5 h^{-1}. In most of the pollution episodes, the maximum concentration of particles in exhaust air was reached within a few minutes. The most rapid increase in particle concentration was during thermal source episodes such as candle, cigarette, incense stick burning and cooking related sources, while the slowest decay of concentrations was associated with sources, emitting ultrafine particle precursors, such as furniture polisher spraying, floor wet mopping with detergent etc. Placement of the particle sensors in the ventilation exhaust vs. in the centre of the ceiling yielded comparable results for both measured maximum concentrations and temporal variations, indicating that both locations were suitable for the placement of sensors for the management of IAQ. The obtained data provides information that may be utilized considering measurements of aerosol particles as indicators for the real-time management of IAQ.

1. Introduction

Indoor air quality (IAQ) is one of the most important parameters determining indoor microclimate and human comfort. Because of the lifestyle induced by the modern society, people tend to spend most of their time in various indoor environments such as home, workplace, or other microenvironments (e.g. transport) (Klepeis et al., 2001). Many earlier studies (Lahtinen et al., 1998; Wallace, 1996; Jones, 1999; Bekö et al., 2013; Morawska et al., 2013; Wierzbicka et al., 2015) have shown that the air in closed environments is frequently more contaminated than the outdoor air. These contaminants include a wide range of organic and inorganic substances in gaseous and particle phases (Lewis and Gordon, 1996). Exposure to these pollutants, especially fine (<1 μm) and ultrafine (<0.1 μm) airborne particles, has been identified as an important factor affecting human health (Alvin et al., 2000; Schwartz et al., 1996; Seaton et al., 1995; Jones, 1999; Dockery,

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2009; Weichenthal et al., 2007).

A large fraction of indoor air pollution results from the penetration of outdoor pollutants indoors. At the same time, the indoor environments contain their own sources of pollution (WHO, 2005). These sources are commonly classified to categories such as food preparation, furniture, building materials, heating, combustion, and humans themselves (Afshari et al., 2005; Wallace, 2006; He et al., 2004; Zai et al., 2006). They may also be classified based on their temporal variation, i.e. the rate of emission in time. Sources having rapid temporal variation may be referred as active sources (Hussein et al., 2006), such as cooking, smoking, indoor combustion, heating, use of personal care products, and application of household chemicals. The emission from building materials have a relatively slow temporal profile, thus may be referred as passive sources (Kelly et al., 1999; Jones, 1999).

Besides their temporal variation, the pollution sources may be classified by their characteristic pollutants, such as PM (ultrafine, fine, and coarse), volatile organic compounds (VOCs, several thousands of gaseous-phase hydrocarbons), carbon dioxide, nitrogen oxides, etc. Often, active emission sources emit a combination of pollutants, however, large emissions of PM has been associated with the most of active sources. Food preparation activities have been reported as substantial emitters of ultrafine particles (<0.1 μm, UFP) and fine particles (from 0.1 to 2.5 μm, FP) (Afshari et al., 2005; Géhin et al., 2008; Glytsos et al., 2010; Torkmahalleh et al., 2012; Buonanno et al., 2009). Combustion sources such as candle and incense burning have been identified as emitting particles in the diameter range of 0.03–3 μm (Fine et al., 1999; Weschler and Nazaroff, 2008; Morawska and Zhang, 2002; Pagels et al., 2009; Isaxon et al., 2013; Stabile et al., 2012). Emissions from tobacco smoking have attracted considerable attention as both source of particles and VOCs (Brauer et al., 2000; Jones, 1999; Afshari et al., 2005; Glytsos et al., 2010; Hussein et al., 2006; Wu et al., 2012). Air-freshener spray also produces substantial amount of PM (Afshari et al., 2005), due to reaction of VOCs with ozone that lead to nucleation of UFP (Nazaroff and Weschler, 2004). Vacuum cleaners operating with or without dust bags have also been shown to produce PM in a size range above 0.3 μm (Lioy et al., 1999).

Real-time IAQ measurement emerges as one of viable strategies to assure high IAQ, especially considering tightening building envelopes in low energy buildings. Although active indoor PM sources have been extensively characterized, there is still a lack of dynamic characteristics needed to facilitate management of IAQ based on the variations of PM concentration. IAQ has been managed based on the sensors of CO_2 (Fisk and Almeida, 1998), and more recently, VOCs (Kolarik, 2012), Many recent studies have reported the effects of ventilation to the indoor PM concentrations (Ai et al., 2015; Fischer et al., 2015; Guo et al., 2008), but the opposite – usage of PM sensor data control ventilation – has not been reported previously. Although there are some commercial attempts to include PM (i.e. Intwine Connect, LLC), such applications have not yet been supported by scientific studies. PM is a specific pollutant with numerous indoor pollution sources may be and often are different than of VOCs and CO_2. Moreover, PM emitted from various sources in various indoor microenvironments may cause different health effects (Bekö et al., 2015). The removal mechanism of PM in indoor environments may also be different compared to VOCs and CO_2, e.g., ventilating through windows may not be effective to remove PM (Kim et al., 2014). In order to obtain effective application of engineering measures (such as ventilation and air cleaning) for the improvement of IAQ, the pollution sources need to be uniformly characterized for their profiles with respect to emission intensity and temporal patterns.

This study aims at the characterization of the dynamics of various common active indoor pollution sources with respect to particle concentration variation in two locations within a simulated room. The database has been built with the parameters describing PM concentration variation in time. The data obtained in the study is discussed via the point of view of modelling and managing IAQ.

2. Materials and methods

2.1. Tested indoor sources and the chamber

The most common active pollution sources were selected based on the earlier reported studies and classified into four main categories: cooking related sources (Hussein et al., 2006; Brauer et al., 2000; Afshari et al., 2005), other thermal sources (Wu et al., 2012; Isaxon et al., 2013; Fine et al., 1999; Pagels et al., 2009; Morawska and Zhang, 2002), personal care products (Nazaroff and Weschler, 2004; Géhin et al., 2008), and household sources (Glytsos et al., 2010; Weschler and Nazaroff, 2008; Lioy et al., 1999; Jones, 1999). The studied pollution sources and testing conditions are explicitly listed in Table 1.

Simulations were carried out in a test chamber with the floor area of 13 m^2 and volume of a 35.8 m^3, representing a typical room, which was installed inside of 150 m^3 laboratory premises (Jurelionis et al., 2015). The distance from the chamber floor to the air supply diffuser was 2.3 m and 2.8 m to air exhaust diffuser (equal to chamber height). The distance between the exhaust and supply diffusers was 2.6 m Fig. 1 shows the schematic diagram of the experimental setup. Walls, floor and ceiling of the chamber were fabricated using conventional construction materials, such as painted dry-wall, PVC floor lining, and a panel ceiling. The ventilation air was supplied via the air handling unit (Gold04, Swegon, Sweden), assuring the air change rate of 0.5 ± 0.1 h^{-1} in the chamber in order to simulate typical ventilation conditions, either in forced or natural mode. Air change rate of test chamber volume was checked before and after of each experiment via the air velocity measurements. Additionally, the air change was verified using CO_2 decay method (ASTM E741). The nozzle diffuser was built from 25 separate nozzles supplying the air downwards at 45° angle to the wall.

Low concentration of PM (<300 p/cm^3) in the supply air was ensured using an F7 class filter (constructed inside the handling unit) and a high efficiency particulate air filter (HEPA 12, General Filter, Italy) installed at the supply diffuser. The temperature (T) and relative humidity (RH) were recorded during the experiments, and ranged from 18 to 22 °C and 30–70% (water boiling experiments), accordingly.

The description of the modelling of each source with the tested procedure is presented in Table 1. After the end of each experiment, the room was purged with air until the concentrations of particles reached the background values (observed values before the initiation of the experiment). Before the start of each run a background concentration of PM was recorded (3 min before the start). Experiments for each source were repeated three times. A pollution episode was generated and the dynamics of particle concentrations were monitored for 30 min. This duration was selected due to the limitation of overall experiment time. Each run required approximately 90 min of purge of the chamber before the start of the experimental run, which lasted for 30 min. The analysis of the results has later indicated that in some cases this period has been insufficient to reduce the concentration of PM back to the background level.

Another specific experiment has been performed in order to test the effect of measurement location to the variation of PM concentrations. Separate measurements for each source were performed in two places: in the exhaust ventilation and in the centre of the ceiling. It was hypothesized that exhaust air should provide an