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Indoor-to-outdoor relationship of aerosol particles inside a naturally ventilated apartment – A comparison between single-parameter analysis and indoor aerosol model simulation

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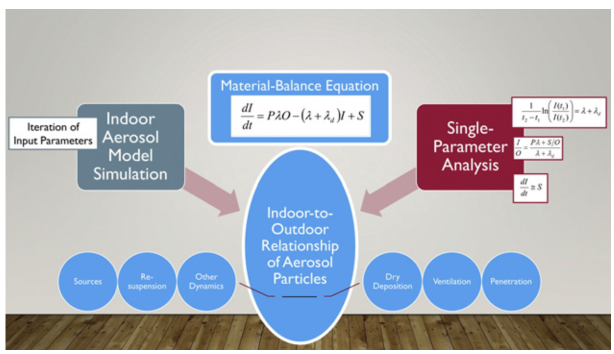
HIGHLIGHTS

- Indoor-to-outdoor relationship of aerosol particles is an important topic.
- Single-parameter analysis can't predict penetration factor and loss/source rates.
- Indoor aerosol model simulation analysis is a superior approach.

GRAPHICAL ABSTRACT



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ABSTRACT

The indoor-to-outdoor relationship of aerosol particles is affected by several mechanisms including penetration, ventilation rate, dry deposition rate and sources. Understanding the effect of these factors is essential for a deeper knowledge of the indoor-to-outdoor relationship. In real-life conditions, it is difficult to analyze these factors in a naturally ventilated environment. In this study, a naturally ventilated and an occupied apartment was used to investigate the indoor-to-outdoor relationship of aerosol particles by applying two different techniques; single-parameter analysis and indoor aerosol model simulation. The indoor aerosol model simulation approach can describe the effect of these factors based on high time-resolution calculations and it is a powerful and robust approach. Single parameter analysis is very simple to apply but it is valid under certain conditions. In the absence of indoor activities (i.e. nighttime) and based on the particle number concentrations, the I/O ratio was <1 during spring but ~1.2 during winter. Based on the indoor aerosol model simulation results for the coarse fraction, the penetration factor (P) was 0.3–1, the ventilation rate (λ) was 0.1–2 h^{-1}, and the deposition rate (λ_d) was ~0.15 h^{-1}. The coarse particles concentration was strongly affected by indoor activities. During extreme mechanical activities (e.g. vacuum cleaning), the concentration increased by a factor of 9 (source strength ~160 particles/h). During children play, the coarse fraction concentration increased by a factor of 3 (source strength ~10 particles/h). Spraying an insect pesticide increased the coarse fraction concentration by a factor of 9 (source strength ~420 particles/h). Water-pipe tobacco smoking produced huge amounts of both micron and submicron particulate matter; it caused the coarse fraction concentration to significantly increase by a factor of 18 (source strength ~140 particles/h). The use of natural gas heater affected the submicron fraction only and did not affect the micron fraction.

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1. Introduction

Nowadays people are more concerned about the air quality they breathe, especially after the World Health Organization (WHO) announcement in 2007 that about 1.5 million people die annually due to poor indoor air quality (WHO, 2007). The WHO also recognized healthy indoor air as a fundamental human right (WHO, 2000). In urban areas, the concern goes beyond the outdoor air quality, which is affected by anthropogenic activities such as traffic and industrial emissions. In fact, the people living in urban areas spend most of their time in closed environments such as apartments, offices, schools, etc. (e.g. Odeh and Hussein, 2016; Hussein et al., 2012a; Schwerizer et al., 2007; Klepeis et al., 2001; McCurdy et al., 2000). However, their indoor activities produce a burden on their health due to their exposure to anthropogenic contamination with concentrations that are usually several times higher than those found outdoors (e.g. Hussein et al., 2015b; Morawska et al., 2013; Sangiorgi et al., 2013; Koivisto et al., 2010; Morawska et al., 2009; Wensing et al., 2008; He et al., 2007, 2004; Ren et al., 2006; Afshari et al., 2005; Jones, 1999).

There is a growing need for indoor-outdoor aerosol measurement campaigns (Morawska et al., 2013). Reporting the results of these campaigns should not only include indoor aerosol concentrations, but also how these concentrations are accumulating indoors from both indoor and outdoor sources. In other words, we need to understand the indoor-to-outdoor relationship of aerosol particles (Hussein et al., 2015b). A key question here is, "how to reduce the migration of harmful air pollutants from the outdoor air into the indoor air?" Another key question here is, "how to reduce the production of harmful air pollutants from indoor sources?" Both key questions lead to the important question of "how to improve the indoor air quality?" (De Gennaro et al., 2014). The indoor-to-outdoor relationship of aerosol particles is mainly affected by four mechanisms: penetration from outdoors (i.e. filtration and infiltration), indoor-outdoor air exchange rate, deposition rate onto indoor surfaces, and indoor sources and re-suspension (e.g. Kubota and Higuchi, 2013; Buonanno et al., 2012; Shaughnessy and Vu, 2012; Hussein and Kulmala, 2008; Ferro et al., 2004; Nazaroff, 2004). Normally, the dynamic behavior of indoor aerosols is not often that simple and it might include complex processes such as gas-particle interaction, condensation/evaporation, coagulation, etc. (e.g. Hussein and Kulmala, 2008; Nazaroff, 2004).

The bottom line here is that indoor-outdoor aerosol measurement campaigns produce data-bases that can be evaluated for the assessment of indoor-to-outdoor relationship of aerosols. Interpretation of the results is influenced by the method (i.e. model approach, data analysis, etc.) used and the user applying the evaluation of the data-base (e.g. Hussein et al., 2011). This manuscript is dedicated to present two commonly used approaches in the investigation of the indoor-to-outdoor relationship of aerosols. The two approaches are; single-parameter analysis and indoor aerosol modeling. A naturally ventilated occupied apartment will be used as a case study where these two approaches will be applied to investigate the indoor-to-outdoor relationship of aerosol particles.

2. Materials and methods

2.1. The material-balance equation

The material-balance equation describes the dynamic behavior of indoor aerosols. It is mathematically written in the form

$$\frac{dI}{dt} = P\lambda O - (\lambda + \lambda_d)I + S \tag{1}$$

where I and O are the aerosol particle concentrations indoors and outdoors, respectively. P is the penetration factor of aerosol particles when they are transported from the outdoor air into the indoor air, λ is the ventilation rate, λ_d is the deposition rate onto available indoor surfaces. Sometimes, aerosol particles are produced or emitted indoors; that is represented by the source rate term S.

The material-balance equation must satisfy two main conditions: (1) the indoor air is well-mixed and (2) it is valid for a certain particle size fraction that has similar chemical-physical characteristics. It is possible to find an analytical solution for the mass-balance equation when the outdoor concentration (O) and the source term (S) as well as P, λ, and λ_d are all constants

$$I(t) = I_0 e^{-(\lambda+\lambda_d)t} + \frac{P\lambda O + S}{\lambda + \lambda_d}\left[1 - e^{-(\lambda+\lambda_d)t}\right] \tag{2}$$

where I_0 is the indoor concentration at $t = 0$.

2.2. Indoor-to-outdoor relationship of aerosol particles

The indoor-to-outdoor concentration (I/O) ratio is often used as an indicator for the source origin of indoor aerosols (e.g. Hussein et al., 2005; Hussein et al., 2006). During steady-state conditions (i.e. the change rate of indoor aerosol concentration is zero), Eq. (2) yields the I/O ratio as

$$\frac{I}{O} = \frac{P\lambda + S/O}{\lambda + \lambda_d} \tag{3}$$

which depends on the ventilation rate (λ), the deposition rate (λ_d), the penetration factor (P), and the sources term (S).

The main objective for the prospective researcher is to calculate the I/O ratios and interpret the indoor-to-outdoor relationship of aerosols in terms of λ, λ_d, P, and S. Here we can apply two main approaches. The first approach (Approach I) is single-parameter analysis based on certain conditions to be satisfied to meet the analysis requirements. The second approach (Approach II), which is favored but demanding, is the indoor aerosol model simulation. Approach I often provides misleading results that might lead to false conclusions about λ, λ_d, P, and S. Approach II is a robust tool that provides more realistic results about λ, λ_d, P, and S.

2.3. Approach I: single-parameter analysis

In the single-parameter analysis, the parameters P, λ, λ_d, and S are quantified separately. However, this approach is influenced by the user due to higher chance of human error (e.g. Hussein et al., 2011).

Recalling Eq. (3), we conclude that in the absence of indoor sources ($S = 0$), the I/O ratios are <1 and proportional to P

$$P \propto \frac{I}{O} \tag{4}$$

Once an indoor activity is going on, the I/O ratios exceed 1. When S is the dominant term on the right hand side of Eq. (1), then

$$S \cong \frac{dI}{dt} \tag{5}$$

When the particle concentrations indoors are higher than those outdoors (i.e. $I > O$) right after an indoor activity, then Eq. (1) can be used to calculate ($\lambda + \lambda_d$)

$$\lambda + \lambda_d = \frac{1}{t_2 - t_1} \ln\left(\frac{I(t_1)}{I(t_2)}\right) \tag{6}$$

where $t_2 - t_1$ is the time period chosen during the indoor concentration decay (from $I(t_1)$ to $I(t_2)$) just after an indoor activity is stopped.