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Indoor Aerosol Modeling: Basic Principles and Practical Applications

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Abstract The type and amount of indoor air pollutants affects the comfort and quality of indoor environments. Therefore, indoor air quality is an important issue with different social, economic, and health aspects because people in developing countries spend most of their time indoors being exposed to different kinds of indoor pollutants. The indoor air quality can be assessed empirically by measuring the pollutant concentrations or can be predicted by means of mathematical models. An indoor aerosol model describes the dynamic behavior of indoor air pollutants. The basic concept of indoor air models is the mass-balance-conservation where several factors that govern the indoor particle concentrations can be described. These factors may include direct emissions from indoor sources, outdoor aerosol particles penetrating indoors as a result of the ventilation and filtration processes, deposition onto indoor surfaces, and removal from indoor air by means of ventilation. Here we present principles of indoor aerosol models and we also give examples of different kind of models.

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1 Introduction

An air pollutant can be a gas or an aerosol particle including solid, liquid, radioactive, bio-aerosols, etc. Indoor air pollutants are either generated indoors or transported from the outdoor (Jones 1999). The change rate of an indoor pollutant concentration is therefore governed by sources and sinks. While pollutants are exchanged between the indoor and outdoor air their concentrations are reduced by filtration/infiltration and loss mechanisms such as deposition onto duct lines, building shell, and indoor surfaces. Re-suspension and emissions of pollutants increase their concentrations indoors. In general, the concentrations and dynamic behavior of indoor aerosols can be predicted by means of indoor aerosol models. An indoor aerosol model must, at least, incorporate the most relevant processes such as indoor-outdoor air exchange, penetration, and deposition processes; therefore, we will recall them as the *controlling parameters*. An indoor air model may, additionally, incorporate deposition and re-suspension processes as well as emissions due indoor activities (Kulmala et al. 1999).

A simple indoor aerosol model describes the dynamic behavior of one type of air pollutants in a single compartment. Simple indoor aerosol models are the base-block of more complicated indoor aerosol models and they have been commonly used in literature to predict total number or mass concentrations of aerosol particles, radioactivity concentrations of radon gas, or fate of bio-aerosols indoors (e.g. Jamriska et al. 2003; Riley et al. 2002; Kulmala et al. 1999; Raunemaa et al. 1989; Alzona et al. 1979; Lum and Graedel 1973). We can easily extend a simple indoor aerosol model to describe the dynamic behavior of several indoor pollutants; i.e. multiple-component approach. The change rate of each component concentration must be therefore described separately. In principle, indoor pollutants do interact with each others through chemical reactions, disintegration, aerosol dynamics, etc. A common example of multiple-component indoor air models is the sectional (size-resolved) indoor air model in which the dynamic behavior of indoor particle size distributions is the main interest (e.g. Asmi et al. 2004; Nazaroff 2004; Thatcher et al. 2002; Long et al. 2000; Abt et al. 2000; Thatcher and Layton 1995).

In real life situations, dwellings consist of several rooms/floors in addition to a mechanical ventilation system (fresh and exhaust air sections and sometimes a recycled air section) or the indoor pollutant concentrations may show spatial gradients, therefore, a single-compartment indoor air model is no longer valid. Multiple-compartment and size-resolved indoor aerosol models are introduced to describe the dynamic behavior of aerosol particles within a dwelling or large halls. Multiple-compartment and size-resolved indoor air models are very complicated and numerically demanding. MC-SIAM and MIAQ are multiple-compartment and size resolved indoor aerosol models that incorporate aerosol dynamics (Hussein et al. 2005b, 2006; Miller and Nazaroff 2001; Nazaroff and Cass 1989, 1986). Several multiple-compartment and size-resolved indoor aerosol models can be found in literature (e.g. Thornburg et al. 2001; Mosley et al. 2001; Schneider et al. 1999; Tung et al. 1999).

In this paper we will present and discuss the basic principles and development of different types of indoor aerosol models, their accuracy, and some practical applications. Our discussion will be specific for indoor aerosol particles only.

2 Mathematical Formulation

The change rate of indoor aerosol particle concentrations in a compartment, k, and a particle size-section, i, is described by the balance-equation in a compact form

$$\frac{d}{\mathrm{d}t} N_{k,i} = \sum_{l} J_{k,i}^{(l)} \tag{1}$$

where $N_{k,i}$ is the number concentration (m^{-3}) of particles in the compartment k and size-section i. On the right side of the equation, J denotes the change rate of particle number concentration ($\mathrm{m}^{-3}\ \mathrm{s}^{-1}$) due to processes ($l$); (see also Fig. 1):

- Indoor–outdoor air exchange, penetration, filtration, and infiltration processes.
- Internal air exchange processes between indoor compartments.
- Deposition processes of aerosol particles on indoor surfaces.
- Resuspension process.
- New particle formation (nucleation) and emission processes.
- Other aerosol dynamics: condensation, evaporation, coagulation, etc.

Depending on the situation and time scale of different processes, some of these processes may become negligible and the indoor aerosol model gets simpler. Following is a detailed description and discussion on these processes.

2.1 Indoor–Outdoor Air Exchange, Filtration, and Infiltration Processes

As mentioned before, indoor aerosols are governed by sources and sinks. Sources of indoor aerosols can be either of indoor or outdoor origin. Aerosols of outdoor origin penetrate into the indoor air as a result of the indoor-outdoor air exchange processes. There are two major methods of indoor-outdoor air exchange: Mechanical ventilation and natural ventilation. Mechanical ventilation usually provide a well defined indoor air mixing and velocity fields. Air exchange rate during natural ventilation occurs through an open window or door, air leakage paths

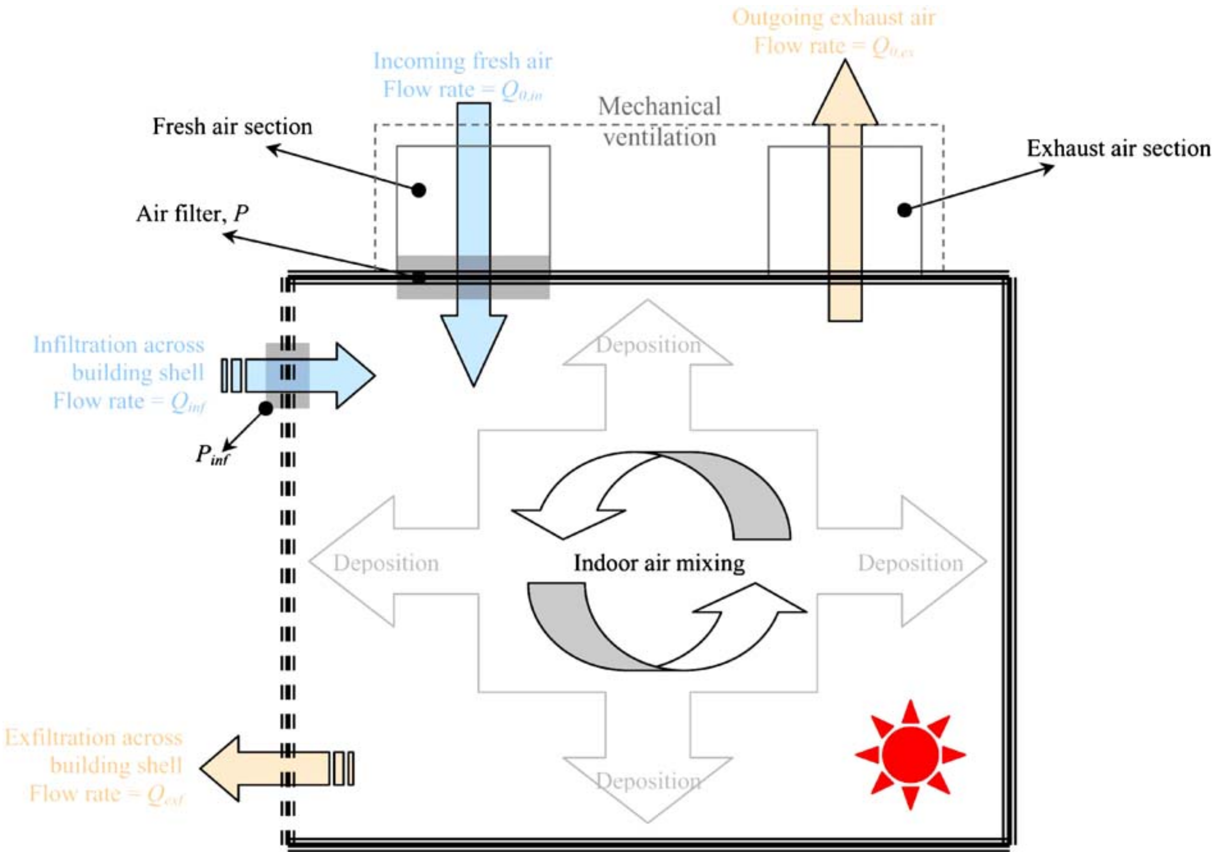


Fig. 1 Sketch of a simple-single compartment indoor aerosol model. The processes included in this simple model are indoor–outdoor air exchange (mechanical ventilation), penetration (air filter), deposition, and sources and resuspension indicated with a *star*. The circulating arrows in the middle of the compartment indicate that the indoor air is well mixed with a turbulent flow

across the building shell, via wall-cracks, or around a window shell.

Contrary to mechanical ventilation, the air exchange rate and the penetration factor are not well controlled during natural ventilation; the air exchange rate is typically governed by several factors such as ambient wind (speed, direction, and turbulence), thermal buoyancy, the size and position of ventilation opening or leakage path, heat source and solar radiation, the conductance of the envelope, etc. (e.g. Li and Delsante 2001; Dascalaki et al. 1996).

The mathematical formulation of the indoor-outdoor air exchange processes for an indoor compartment is simply

$$J_{k,i}^{\mathrm{IO-exchange}} = \frac{1}{V_k}\sum_m Q_{mk}P_{m,i}N_{\mathrm{out},i} - \frac{1}{V_k}Q_{k,\mathrm{removed}}N_{k,i} \quad (2)$$

where V_k is the volume (m^3) of compartment k and the summation is over all pathways that bring outdoor aerosol particles into the compartment, Q_{mk} denotes the air flow rate ($m^3\ s^{-1}$) that brings outdoor aerosol particles with outdoor concentrations $N_{\mathrm{out},i}$ (m^{-3}) via pathway m, $P_{m,i}$ is the penetration factor of aerosol particles via that path, $Q_{k,\mathrm{removed}}$ denotes the removed air flow rate ($m^3\ s^{-1}$), and $N_{k,i}$ is the aerosol particle number concentration (m^{-3}) in compartment k.

The penetration factor is the fraction of incoming outdoor aerosols across the building shell or through the ventilation system into the indoor air (e.g. Riley et al. 2002). In general, the penetration factor is smaller than unity and it depends on the particle size. A maximum in the penetration factor curve is often observed in the particle diameter range 0.1–1.0 μm (Hinds 1999), where neither diffusion nor inertial impaction are efficient filtering mechanisms. For a standard air filter (Fig. 2), the penetration factor can be derived from its filtration efficiency (FE)

$$P_i = 1 - \frac{\mathrm{FE}_i\,\%}{100\%} \tag{3}$$

The filtration efficiency is defined as the fraction of entering aerosols retained by the filter. Penetration across filters depends on air flow rate and dust loading on the filter (Goodfellow and Tähti 2001; Hanley et al. 1994). Across the building shell, i.e. natural ventilation, the penetration factor varies with the building geometry, surface materials, and pressure drop along the leakage path (e.g. Liu and Nazaroff 2001).

2.2 Internal Air Exchange Processes

In a multiple-compartment approach, internal air exchange between compartments can strongly influence indoor aerosol concentrations and it is mathematically written as

$$J_{k,i}^{\mathrm{internal-exchange}} = \frac{1}{V_k} \sum_j \left(Q_{jk} N_{j,i} - Q_{kj} N_{k,i} \right) \tag{4}$$

where Q_{jk} is the air flow rate ($\mathrm{m}^3\ \mathrm{s}^{-1}$) from compartment j into compartment k, and $N_{j,i}$ and $N_{k,i}$ are respectively the aerosol particle number concentrations (m^{-3}) in these compartments. In practice, it is not necessary that Q_{jk} and Q_{kj} are equal. The driving forces of internal air exchange are pressure differences caused by winds, temperature differences, and fan operation.

The internal air exchange between compartments is very difficult to be measured. However, CFD modeling and multiple-compartment air flow models (such as COMIS and CONTAM) provide better understanding on the air flow indoors (e.g. Posner et al. 2003; Ren and Stewart 2003; Haas et al. 2002; Ziskind et al. 2002; Borchiellini and Fürbringer 1999; Feustel 1999; Roulet et al. 1999; Walton 1997; Fan 1995; Gan 1995). However, from the indoor air quality point of view, internal air exchange has received too little attention; more specifically with respect to indoor particles, a few studies have explored concentration variability among rooms and the factors that influence them (e.g. Hussein et al. 2006; Miller and Nazaroff 2001; Ju and Spengler 1981).

In the context of indoor aerosol modeling, it is important to distinguish between the term "air exchange rate" and the term "ventilation rate". The "air exchange rate" has the units of air volume per unit time (e.g. $\mathrm{m}^3\ \mathrm{s}^{-1}$) and it represents the amount of air that passes through a certain path. The

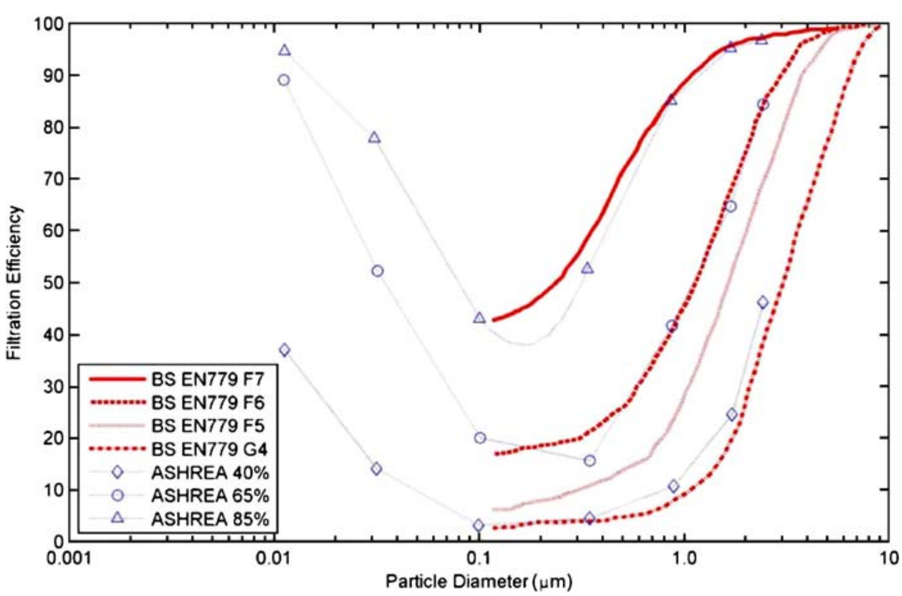


Fig. 2 Filtration efficiencies of standard class filters: ASHRAE standards are adopted from Hanley et al. (1994) at 1.3 m/s face velocity, and BS EN 779 standards are adopted from Goodfellow and Tähti (2001) at the minimum efficiency

"ventilation rate" represents the number of times (e.g. h^{-1}) the indoor air is changed within an indoor compartment. The ventilation rate is simply the ratio between the total air exchange rate and the compartment volume.

2.3 Deposition and ReSuspension Processes

Aerosol particles deposit on available indoor sources. On the other hand, deposited aerosol particles may re-suspend and become airborne again. Deposition of aerosol particles on indoor surfaces is a sink term, i.e. removal process, whereas resuspension process is an indoor source term.

Deposition of aerosol particles occurs as a result of two main mechanisms:

– Advection and turbulent diffusion that rapidly transport particles from the indoor air core to boundary layer.
– Transport through the boundary layer via Brownian and turbulent diffusion, inertial impaction, and gravitational settling.

Diffusion is the dominant mechanism for ultra-fine particles whereas gravitational settling and impaction are the dominant processes for coarse particles. Electrostatic and thermostatic mechanisms are believed to be negligible (e.g. Lai and Nazaroff 2000). Aerosol particle deposition varies with the type and surface area of indoor surfaces (e.g. Howard-Reed et al. 2003; Lai et al. 2002; Thatcher et al. 2002; Abadie et al. 2001; Fogh et al. 1997; Porstendörfer and Reineking 1992; Nazaroff and Cass 1989).

A fraction of aerosol particles deposited onto surfaces may re-suspend and become airborne due to ordinary indoor activities including walking and housekeeping. Such ordinary activities may also generate and suspend new particles as a result of surface wear. The resuspension process is, however, not yet well understood. Only few studies considered this process (e.g. Ferro et al. 2004; Theerachaisupakij et al. 2003; Friess and Yadigaroglu 2002; Kulmala et al. 1999; Kildeso et al. 1999; Lazardis and Drossinos 1998; Thatcher and Layton 1995). So far there is no generalized approach that can be utilized in indoor aerosol models. Usually, due to the complexity and the lack of experimental data, the resuspension process is handled as source term in the balance-equation.

The deposition and resuspension processes of aerosol particles can be expressed mathematically according to

$$J_{k,i}^{\mathrm{Dep.-Re}} = -\frac{1}{V_k}\sum_j A_{kj} v_{kj,d,i} N_{k,i} + \frac{1}{V_k}\sum_j f_{kj,i} A_{kj} \lambda_{kj,re,i} B_{kj,i} \qquad (5)$$

where the first term is the deposition term: A_{kj} is the total area (m^2) of the deposition surface j in compartment k. The deposition velocity, $v_{kj,d,i}$ (m s^{-1}) can be estimated from deposition models (e.g. Corner and Pendlebury 1951; Nazaroff and Cass 1989; Lai and Nazaroff 2000). The second term is the resuspension term according to Asmi et al. (2004): $B_{kj,i}$ is the aerosol particle concentration (m^{-2}) accumulated on an indoor surface j of area A_{kj} (m^2); A fraction $f_{kj,i}$ of the accumulated particles are available for re-suspension from the surface with a re-suspension rate $\lambda_{kj,re,i}$ (s^{-1}). "i" denotes that the equation is valid for a certain size-section.

Consequently, the balance-equation that describes the change rate of aerosol particle number concentrations on an indoor surface is

$$A_{kj}\frac{d}{dt}B_{kj,i} = A_{kj} v_{kj,d,i} N_{k,i} - f_{kj,i} A_{ki} \lambda_{kj,re,i} B_{kj,i} \qquad (6)$$

where $B_{kj,i}$ is the surface particle concentration accumulated on an indoor surface i in the compartment k. Eq. 1 and Eq. 6 are solved simultaneously for the particle number concentrations $N_{k,i}$ and $B_{kj,i}$.

2.4 Other Aerosol Dynamic Processes: Condensation/Evaporation, Coagulation, Nucleation

The evolution of aerosol particle size distribution takes place via condensation, evaporation, coagulation, chemical reactions, etc. However, chemical reactions are not fully understood in indoor aerosols. Condensation/evaporation and coagulation processes are usually well understood and therefore they can be incorporated in indoor aerosol models.

The compounds leading to new particle formation (e.g. nucleation processes) have remained unsolved in the indoor air. For example, fine particles may consist of significant amounts of soot, metals, and organic compounds. A common example of new particle formation in the indoor air is accompanied with pealing citrus fruits that releases terpens in the atmosphere. This produces significant amounts of aerosol particles that grow from the very small sizes bellow 0.01 μm to the Aitken mode between 0.025–0.1 μm (e.g. Vartiainen et al. 2006). On the other hand, cooking usually generates different kinds of vapors that stimulate secondary particle formation in the indoor air.

In literature can be found several aerosol dynamics models that can be integrated in indoor air models; few to mention: "University of Helsinki Multi-component Aerosol model" – UHMA – (Korhonen et al. 2004), AEROFOR (Pirjola 1999), and the integrated aerosol dynamic model described by Nazaroff and Cass (1989, 1986).

2.5 Indoor Sources of Aerosol Particles

As mentioned before, indoor aerosol particles are governed by sources that are either of indoor or outdoor origin. Indoor sources are usually due to inhabitant's activities. Indoor coarse particles tend to be produced by mechanical means. Bio-aerosols including allergens, fungi, bacteria, and viruses can be either coarse or fine (e.g. Meklin et al. 2002; Lee et al. 2002; Otten and Burge 1999; Wanner 1993; Platts-Mills et al. 1991). Indoor fine particles are generated by means of gas-to-particle conversion processes that are often associated with high temperature during combustion and cooking.

Even though many studies discussed indoor sources of aerosol particles only a few focused on the particle number size distributions and even very few presented quantitative determination of aerosol particle emissions from indoor sources (Hussein et al. 2005a, b, 2006; Afshari et al. 2005; He et al. 2004; Fan and Zhang 2001).

3 Mathematical Solutions of Indoor Aerosol Models: Some Practical Applications

The required input variables to simulate or predict the concentrations of indoor aerosols are: the aerosol particle concentrations in the outdoor air, penetration factor (or filtration efficiency), ventilation rate (or air exchange rate), deposition rate (or deposition velocity), dwelling geometries (volume, internal surface area including walls, ceilings, floors, and furniture), internal air-exchange rates between indoor compartments, and a diary of indoor activities. All these input parameters and variables are set up for a mathematical solution that solves for indoor particle concentrations in each size-section and each compartment, $N_{k,i}$.

Consider a single compartment dwelling and assume that

- The indoor air is well mixed,
- Penetration factor, ventilation rate, and deposition rate are all constant,
- The aerosol particle concentration is rather constant in the outdoor air,
- The indoor source has a constant emission rate,
- The re-suspension process is negligible, and
- Condensation/evaporation and coagulation processes are also negligible.

The common mathematical formulation for a simple sectional indoor aerosol model (e.g. Jamriska et al. 2003; Riley et al. 2002; Mosley et al. 2001; Kulmala et al. 1999)

$$\frac{d}{dt}N_{in,i} = \lambda P_i N_{out,i} - \left(\lambda + \lambda_{d,i}\right)N_{in,i} + S_{in,i} \qquad (7)$$

Where $N_{\mathrm{in},i}$ (cm^{-3}) and $N_{\mathrm{out},i}$ (cm^{-3}) are respectively the indoor and outdoor particle number concentrations indoors and outdoors, P_i is the penetration factor, λ (s^{-1}) is the ventilation rate, $\lambda_{d,i}$ (s^{-1}) is the deposition rate of aerosol particles on indoor surfaces, and $S_{\mathrm{in},i}$ ($\mathrm{cm}^{-3}\ \mathrm{s}^{-1}$) is the sources of aerosol particles in the indoor air.

The analytical solution for this simple indoor air model can be easily verified in the form

$$N_{\mathrm{in},i}(t) = N_{0,\mathrm{in},i}e^{-\left(\lambda+\lambda_{d,i}\right)t} + \frac{\lambda P_i N_{\mathrm{out},i} + S_{\mathrm{in},i}}{\lambda + \lambda_{d,i}}\left(1 - e^{-\left(\lambda+\lambda_{d,i}\right)t}\right) \qquad (8)$$

where $N_{0,\mathrm{in},i}$ is the initial concentration (at time t=0) of the indoor aerosol particles within size-section i.

Indoor and outdoor aerosol particle concentrations may maintain steady-state conditions after a certain time period (i.e. long enough time period) when the outdoor aerosol concentrations are rather constant. For example, if we further assume that indoor sources of aerosol particles are negligible; i.e. $S_{\mathrm{in},i} << \lambda P_i N_{\mathrm{out},i}$, then the so called indoor-to-outdoor concentration (I/O) ratio is

$$I/O|_i = \left.\frac{N_{\mathrm{in},i}}{N_{\mathrm{out},i}}\right|_{\mathrm{Steady-State}} \cong \frac{\lambda P_i}{\lambda + \lambda_{d,i}} \tag{9}$$

The steady-state level for the I/O ratio is maintained after a certain time period, which is inversely proportional to the ventilation rate. Empirically, the instantaneous I/O ratio can be evaluated from the measured indoor and outdoor particle concentrations after elimination of the time-lag between their temporal variations (e.g. Morawska et al. 2001). The difference between the temporal variations of the indoor and outdoor particle concentrations is known as the time-lag. Note that a steady-state condition might not be maintained during ventilation rates bellow 1.5 h^{-1} when the outdoor particle concentrations vary rapidly. On the other hand, during high ventilation rate (e.g. >3 h^{-1}) the steady-state condition can be maintained easily and the I/O ratio is expected to be equal to the penetration factor if the deposition rate is negligible in comparison to the ventilation rate, i.e. according to Eq. 9.

$$\left.\frac{N_{\mathrm{in},i}}{N_{\mathrm{out},i}}\right|_{\mathrm{Steady-State}} \xrightarrow{\lambda >> \lambda_{d,i}} P_i \tag{10}$$

Here we come to a very important point where we have to distinguished between the I/O ratio, the infiltration factor (INF), and the penetration factor (*P*). As stated before, the penetration factor is the fraction of aerosol particles that pass across the building shell or via the ventilation system into the indoor air and it is less than unity. The INF is defined as the equilibrium fraction of ambient aerosol particles that penetrate indoors and remain suspended (Long et al. 2000); this is regardless to the air-exchange path. By definition, indoor sources of aerosol particles do not contribute to the INF, but they do contribute to the I/O ratio. The I/O ratio and the INF are equivalent only when indoor sources are negligible; they are both influenced by three main parameters: penetration factor, ventilation rate, and deposition rate (Kulmala et al. 1999). In other words, the value of the INF varies between 0 and 1 whereas the I/O ratio can have any value larger than zero. The INF and the I/O ratios are the most important terms to determine whether the indoor aerosol particles are of indoor or outdoor origin. On the other hand, the penetration factor is the most important parameter controlling the indoor air quality when the indoor aerosol particles are of outdoor origin.

3.1 Numerical Simulations

Before starting any numerical simulations, the indoor-to-outdoor relationship of aerosol particles should be evaluated. The time periods of indoor activities should be eliminated for this stage of the analysis. The I/O ratios can be first represented by their medians and percentiles (Hussein et al. 2005a) to be used later as initial guess for the penetration factor.

The second stage is to evaluate the particle deposition rate in the indoor domain according to the analytical solution in Eq. 8: follow the decreasing pattern of indoor particle concentrations right after an indoor source that was terminated at a certain time. The indoor source is assumed to generated huge amounts of aerosol particles that are significantly higher than the outdoor particle concentrations; i.e. $N_{\mathrm{in},i} >> N_{\mathrm{out},i}$. The aerosol particle concentrations decrease as a result of the removing processes (ventilation and deposition) and after a time period Δt of the indoor source termination, Eq. 8 can be approximated to the form

$$\lambda_{d,i} + \lambda \cong \frac{1}{\Delta t} \ln\left(\frac{N_{\mathrm{in},i}(t_0)}{N_{\mathrm{in},i}(t_0 + \Delta t)}\right) \tag{11}$$

Using events with known ventilation rate, the particle deposition rate can be estimated. If the ventilation rate is unknown, it can be estimated from Eq. 11 when applied for particles between 0.1 and 1.0 μm in diameter. Typically, the deposition rate of aerosol particles in that diameter range varies between 0.02 and 0.1 h^{-1} and can be neglected with ventilation rates higher than 0.5 h^{-1} (Nazaroff 2004). Figure 3 presents the particle deposition rate as reported by previous studies.

Once the indoor-to-outdoor relationship of aerosol particles is evaluated, we can easily determine the optimal values of the penetration factor, ventilation rate, and deposition velocity. Numerically, the optimal value of a parameter can be estimated by iterating its input value until the best-match is achieved between the measured and simulated indoor particle number size distributions. The penetration factor can be therefore iterated between 0 and 1 for all particle sizes with an initial guess equal to the I/O ratio. Hussein et al. (2006) showed that the penetration

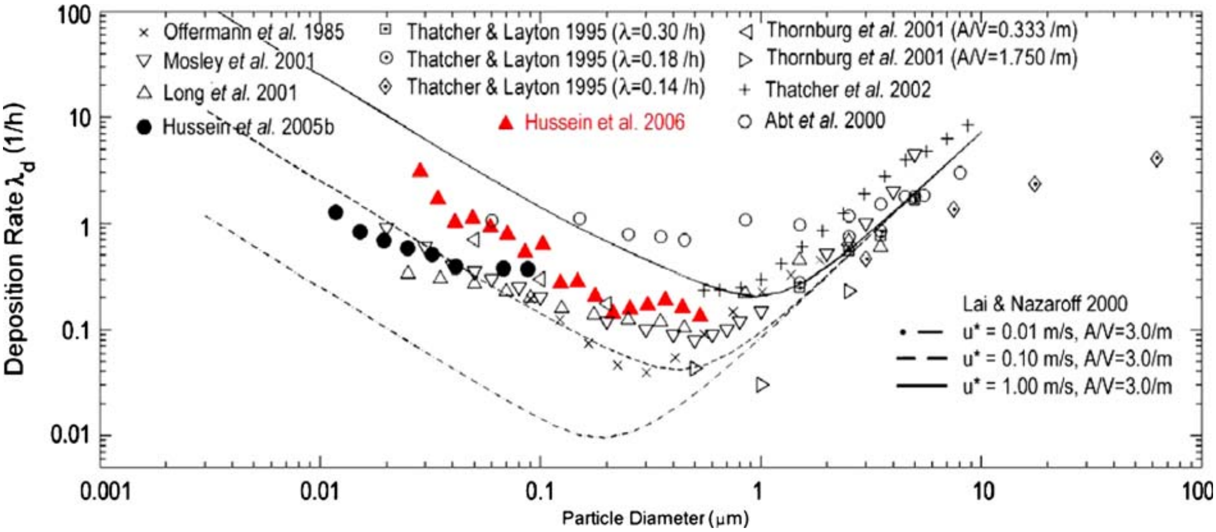


Fig. 3 Particle deposition rates reported in previous studies. The lines represent calculated deposition rates using the model by Lai and Nazaroff (2000): A/V is the total indoor surface area to the total room volume ratio and u* is the friction velocity

factor for their guest apartment varied between the 25th percentiles of the I/O ratio. In the same study, the optimal value of the ventilation rate varied between 0.6 and 1.2 h^{-1} (measured value 0.27–0.61 h^{-1}). The optimal value of the friction velocity was 10–30 cm/s. Following similar procedure, the optimal curve of the penetration factor was also estimated for an office room and a family house as illustrated by Hussein et al. (2005b).

To illustrate a numerical simulation example we picked up one of our previous measurements in an office room (Hussein et al. 2005b), which consists of a small shower room (2/9 the volume), small bathroom (1/9 the volume), and working office place (2/3 the volume). The total volume of that office room was about 32 m^3 with surface-to-volume ratio of about 2.63 m^{-1}. The office room was ventilated mechanically with a ventilation rate ~3 h^{-1} and G3-class filter. Figures 4 and 5 illustrate the simulation of the indoor particle number concentrations by using a friction velocity 17 cm/s for the deposition model by Lai and Nazaroff (2000); note that the simulation

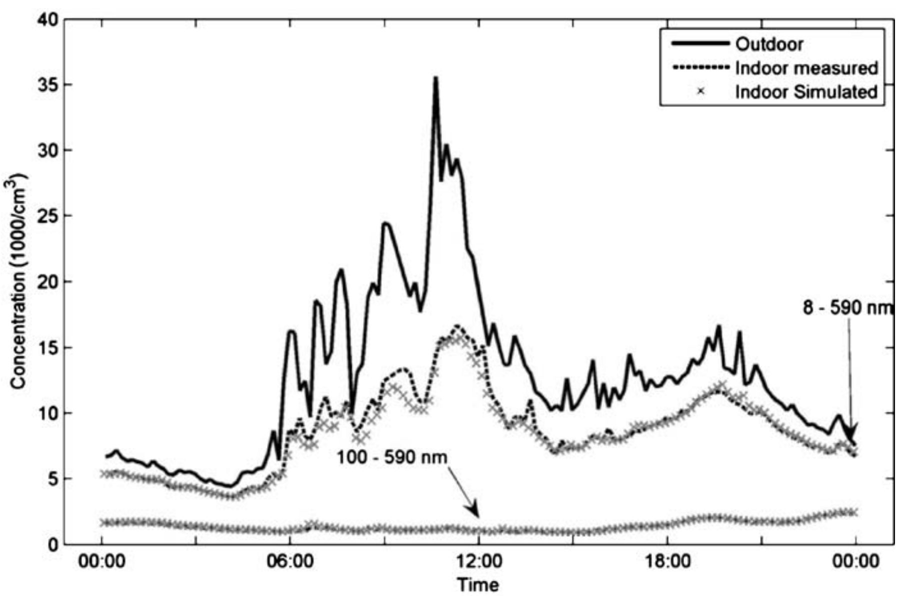
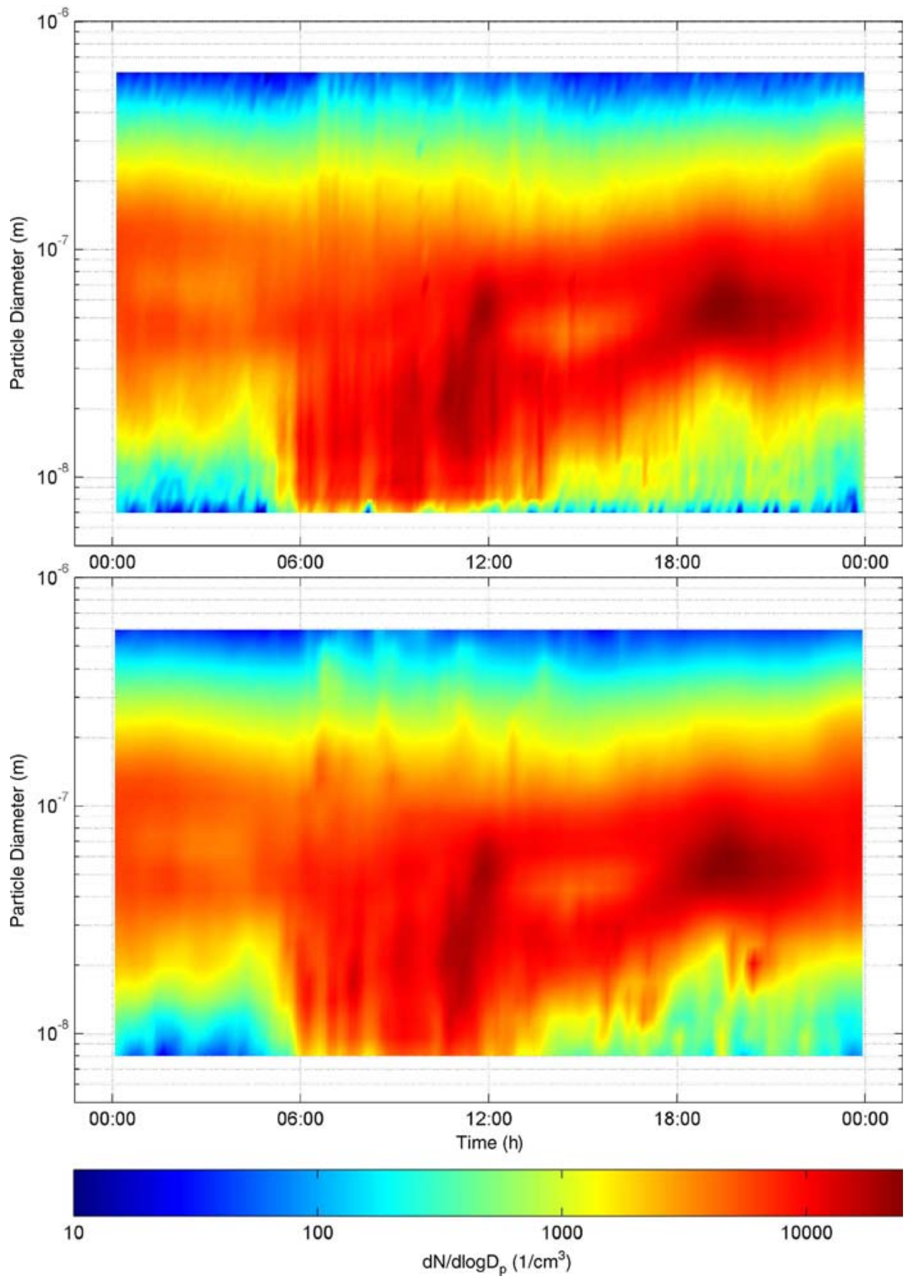


Fig. 4 Simulation of indoor particle number concentrations for an office room: total volume 32 m^3, surface-to-volume ratio 2.63 m^{-1}, mechanically ventilation 3 h^{-1}, G3-class filter, friction velocity 17 cm/s. Note that the simulation was based on single-compartment and sectional approach for the particle diameter range between 8 and 590 nm and the figure presents the particle number concentrations within the size ranges indicated on the figure

Fig. 5 Simulation of indoor particle number concentrations for the same case presented in Fig. 4, here we present the whole number size distribution of indoor aerosol particles (*upper*) measured and (*lower*) simulated



was based on single-compartment and sectional approach for the particle diameter range between 8–590 nm. It seems that a single compartment approach with the measured parameters and the guessed friction velocity is therefore suitable to predict the indoor particle number concentrations in that office room. In our example the indoor particle number concentrations are small enough to ignore the coagulation process.

3.2 Semi-Empirical Estimation of Indoor Aerosol Emissions

If we are convinced with our optimal values of the ventilation rate, friction velocity, and the penetration factor, then we can simulate the particle number size distributions by ignoring indoor sources. Evaluating the difference between the measured and simulated concentrations and assume it is equivalent to the airborne aerosol particles due to indoor sources

$$S_{k,i}^{\text{Emitted}} = N_{k,i}^{\text{Measured}} - N_{k,i}^{\text{Simulated}} \tag{12}$$

we can estimate the emission rate term as (Hussein et al. 2005b, 2006)

$$\begin{aligned}\frac{d}{dt}S_{k,i}^{\text{Emitted}} = J_{k,i}^{\text{Emissions}} + J_{k,i}^{\text{Coagulation}} \\ + J_{k,i}^{\text{Condensation}} \\ - \frac{1}{V_k}\sum_j A_{kj} v_{kj,d,i} S_{k,i}^{\text{Emitted}} \\ - \frac{1}{V_k}\sum_l Q_{k,\text{removed}} S_{k,i}^{\text{Emitted}}.\end{aligned} \tag{13}$$

This principle can also provide quantification for aerosol particle losses due to un-identified indoor sinks of aerosol particles, which are indicated by negative values in the emission rate term. Equations 12 and 13 state a semi-empirical principle based on the following: the indoor aerosol particle concentration measurements quantify the suspended aerosol particles resulting from all possible sources and sinks. Similarly, simulations of indoor particle concentrations illustrate the amount of aerosol particles after being engaged in the processes included in the indoor aerosol model. The difference between the measured and simulated particle concentrations provides the initial step to determine the emission rate.

4 Summary and Conclusions

There are two major types of indoor aerosol models: *single-compartment* (single-zone) and *multiple-compartments* (multiple-zone). Single compartment indoor aerosol models are typically used when the indoor pollutant concentrations do not show spatial gradients. If this assumption does not hold, there is a need for a multiple compartment indoor aerosol model. If the indoor aerosol model describes the dynamic behavior of only one pollutant, it is then called *single-component*. Otherwise, it is called *multiple-component*. Our main objective in this paper is to present the basic principles of indoor air models illustrated with some practical applications.

A sectional indoor aerosol model is superior to a simple indoor aerosol model because it provides better understanding about the particle size dependence of aerosol dynamic processes. In general, the accuracy of an indoor aerosol model is limited to the extent of indoor air mixing. Here, “mixing” refers to the dilution, transport, and dispersion of a pollutant within a domain, i.e. compartment. Mixing is driven by mechanical means (e.g. mechanical ventilation), flow through an open window (e.g. natural ventilation), or movement of people within a room. Temperature gradients among the indoor air parcels can induce convection that induces mixing too.

Simulation of indoor aerosol particles is very challenging. The estimation of the optimal parameters should be performed with great care based on good understanding on the indoor-outdoor relationship of aerosol particles. There can be several sets of optimal parameters that lead to the same acceptable model simulation results. However, a good understanding about the indoor-outdoor aerosol problem helps us to determine the most suitable set of optimal parameters. On the other hand, simulation of indoor aerosol particles is very difficult during indoor activities because of the lack of information about the physical-chemical characteristics of aerosol particles generated during indoor activities.

The accuracy of a sectional indoor aerosol model is limited to the description of the dynamic behavior of aerosol particles and their size distribution. For example, the penetration and deposition processes are particle-size dependent. Therefore, considering a wide size-range of aerosol particles may under or over estimate the penetration or the deposition processes. It is more likely that the physical-chemical characteristics of aerosol particles should be taken into account to better describe their dynamic behavior.

The present indoor aerosol models are able to describe accurate enough most aerosol dynamic processes. However, the new particle formation (see e.g. Vartiainen et al. 2006) in the indoor air cannot be described yet in a proper way. Since, the number concentration of ultrafine indoor aerosol particles are partly determined by new particle formation, also future indoor models should be able to consider nucleation and subsequent growth indoors including recently developed new theories like cluster activation (Kulmala et al. 2006).

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