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Building removal of particulate pollutant plume during outdoor resuspension event

Jing Qian [a,*], Behtash Tavakoli [b], Iman Goldasteh [b], Goodarz Ahmadi [b], Andrea R. Ferro [a]

[a] *Department of Civil and Environmental Engineering, Clarkson University, Potsdam, NY 13699, USA*
[b] *Department of Mechanical and Aeronautical Engineering, Clarkson University, Potsdam, NY 13699, USA*

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ABSTRACT

The capacity of buildings to reduce the outdoor pollutant level during particle transport has not been thoroughly investigated. This study demonstrates that CFD modeling combined with multizone modeling can provide a complete picture on the fate and transport of PM pollutant plume passing a building. A plume intersecting a 6 m × 6 m × 6.3 m building with concentrations of 56, 93, 93, and 74 µg/m^3 for 0.85 µm, 2.63 µm, 3.94 µm, and 8.77 µm particles, respectively, is simulated. The building removal rates are 79 ± 4 mg/h, 182 ± 10 mg/h, 209 ± 12 mg/h, 280 ± 26 mg/h, which are 0.1%, 0.13%, 0.15%, and 0.25% of the plume source emission rates, respectively. The building removal is mainly contributed by the deposition to the building envelope and deposition in the building cracks. The building removal rate varies with particle size, and is more affected by wind direction than the air intake location for the building air handling system. The resulting indoor PM concentration, estimated via multizone modeling, varies with particle size and zone, and is affected by the alignment of building crack openings and wind direction. The demonstrated simulation method can be used to investigate the reduction of a pollutant plume by high-density building clusters in the urban environment as well as the human exposure to the plume indoors. As compared to well-mixed models, the CFD generated spatially-resolved pollutant concentration around the building improves the accuracy of the prediction of indoor exposure to outdoor PM plumes.

1. Introduction

Increased respiratory and cardiac illness and death are associated with elevated levels of inhalable particulate matter (PM) [1–3]. People spend most of their time indoors [4], thus exposure to indoor PM can be a greater risk to occupants' health and performance than outdoor exposure. A significant portion of indoor PM is from outdoor origin, transported indoors via penetration through building cracks, mechanical ventilation, and natural ventilation by opening windows. For example, in homes without any indoor sources and where human activity was low, approximately 70% of indoor PM$_{10}$ is from outdoors [5]. For typical school rooms, outdoor particles contribute 43% and 24% to indoor PM$_{2.5}$ and PM$_{10}$, respectively [6]. The results from the PTEAM study of 178 participants in southern California suggest 70% of indoor PM$_{2.5}$ sulfate are from outdoors [7].

Previous research of indoor PM of outdoor origins has been focused on anthropogenic sources such as factory stack emissions and highway vehicle emissions. Less studied are pollutants of outdoor ground sources, such as outdoor resuspension (i.e., the aerosolization of previously deposited pollutants on the ground), and the subsequent indoor exposure to these particles. When particles are resuspended and carried to a building downwind of the ground source, part of the PM pollutant plume is "taken in" by the building through 1) deposition on the building envelope, 2) removal via deposition in the building cracks, 3) removal by the air handling system (AHS) of the building, and 4) deposition to indoor surfaces. Due to the building removal of a plume, the concentrations of pollutants downwind of a building are reduced to some extent. This building effect on ground-source pollutants can be substantial in urban settings with high density building clusters. In addition, the effect of building removal to indoor air quality (IAQ) for downwind buildings needs to be investigated to understand the pathways of indoor PM of outdoor ground-source origin. Such understanding can facilitate building and interior design to achieve better IAQ and protect human health.

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[*] Corresponding author. Clarkson University, PO Box 5712, Potsdam, NY 13699, USA. Tel.: +1 315 268 2288; fax: +1 315 268 7985.
E-mail addresses: qianjing@clarkson.edu, jjqian@gmail.com (J. Qian).

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The removal of the particles by buildings can be estimated as the sum of particle lost due to deposition to building envelope, removal through building cracks, removal by AHS, and deposition indoors. The removal by building occupants is negligible compared with the removal by the AHS. The inhalation rates for adults are on the order of 16 m^3/day (0.01 m^3/min) [8], much smaller than the minimum outdoor air requirement of 17 cfm (0.48 m^3/min) per occupant, the standard specified for office building by the American Society of Heating, Refrigerating, and Air Conditioning Engineers [9]. Other potentially important factors not investigated in this study include those subject to occupant behavior, e.g., opening windows for natural ventilation, using room air ventilation systems, particles resuspended via human activity, and cleaning indoor surfaces. We expect that the removal rate of PM by the building is a function of particle size, wind direction, and location of air intake of the mechanical air supply system. For IAQ, we expect that the rooms with cracks facing the wind are associated with higher-level of PM concentration of outdoor origin than other rooms of the building.

This study used computational fluid dynamics (CFD) and multizone modeling to simulate the building removal of an outdoor resuspended particle plume. The aerosol distribution around the building envelope is then input to multizone model to predict the increase of indoor inhalable PM level in different zones of a building due to the outdoor PM plume. CFD is used for its accurate prediction and sufficient spatial resolution of aerosol dynamics around buildings [10,11]. Multizone models are based on airflow and mass balance and are computationally much faster than CFD models. The key assumptions for multizone models are uniform pressure, temperature and species concentration within each zone, instantaneous contaminant transport along each flow path, zone pressure not impacted by airflow through zones, and kinetic energy and momentum not accounted for by flow path models [12]. Multizone models have been used in research and design for residential, commercial, and industrial buildings for over 20 years [13–16]. Combining CFD and multizone models can offer detailed information of contaminant dispersion and reduce the computing time [17–20]. This study combines CFD and multizone modeling to investigate the building removal and IAQ. By using a realistic spatially distributed PM concentration and wind flow profile around the building envelope, the simulation improves the spatial resolution and prediction of particle removals at specified building openings (i.e., cracks and air intake).

2. Methods

2.1. Pollutant source and flow simulation

The characterization of the resuspension source is adapted from literature data of Asian dust storms [21]. Fig. 1 shows the reproduced profile of the concentration above the resuspension site. The simulation includes particles of four different diameters, 0.85 μm, 2.63 μm, 3.94 μm, and 8.77 μm, that are resuspended and transported downwind. Assuming a particle density of 2.5 g/cm^3, the corresponding initially resuspended mass concentrations are 56, 93, 93, and 74 μg/m^3, estimated using interpolated number concentration based on the particle profile curve in Fig. 1. The simulated wind speed is 10 m/s. The PM plume encounters a residential building located 58.4 m downwind from the resuspension source.

The airflow around the building is numerically simulated using the commercial code ANSYS FLUENT, and the concentration distribution of the particulate pollution carried to the building by wind flow is modeled for three separate wind directions. The airflow around the building is simulated using the $k-\varepsilon$ turbulence model. Diffusion due to turbulence and Brownian motion are included in the analysis. A total of 330,500 structured grid cells are generated in the CFD simulation, providing a sufficient spatial resolution for the distribution of airflow and PM pollutants around the building, as well as particle deposition on the building surface. A grid sensitivity study is conducted to assess the independency of the numerical simulation results with respect to the grid size. The case with wind direction from north is used for the grid study. For grids of 132000, 260000, 330000, 500000 and 822000 cells, the predicted velocity magnitudes on a line 30 cm above the roof of the building are evaluated and results are compared in Figure S1. It is seen that the computational mesh with 132,000 and 263,000 cells are not able to predict the velocity magnitude accurately when compared with the

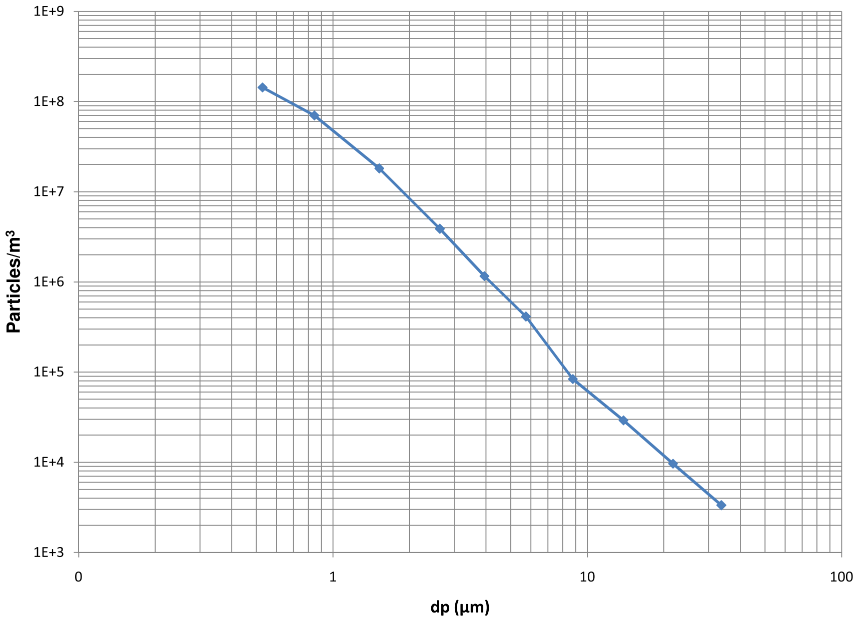

Fig. 1. Particle number concentration by size for resuspended dust particle at the source location outdoors. Data reproduced from Han et al., 2004. The interpolated number concentrations for 0.85 μm, 2.63 μm, 3.94 μm, and 8.77 μm particles are 6.9E + 7, 3.9E + 6, 1.2E + 6, and 8.4E + 4 particles/m^3, respectively. Assuming a particle density of 2.5 g/cm^3, the corresponding initially resuspended mass concentrations are 56, 93, 93, and 74 μg/m^3.