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Numerical investigation on the coupled effects of building-tree arrangements on fine particulate matter ($PM_{2.5}$) dispersion in housing blocks

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ABSTRACT

A numerical simulation using Reynolds-Averaged Navier-Stokes (RANS) model and revised generalized drift flux model was conducted to investigate the coupled effects of different building-tree arrangements on outdoor $PM_{2.5}$ dispersion in housing blocks. Results showed that: 1) trees reduced wind speed according to canopy height and disrupted the airflow field within close vicinity to the canopy, which led to an apparent decrease in $PM_{2.5}$ concentrations within the height of tree crown; 2) horizontal vortex circulation along the building facades produced lower pedestrian-level concentrations behind buildings; 3) buildings that experienced wind deflection on one facade and airflow separation on the other one could get more airflows and benefit from lower $PM_{2.5}$ along vertical building facades; 4) aerodynamic effects of trees did not conquer over the deposition effects in all investigated cases due to the different tree-building arrangements; and 5) the configuration that had dispersed trees and two parallel rows of buildings, which were perpendicular to the prevailing wind, could form more vortex circulations as a result of decreasing concentrations. These results provided an evaluation index for the architectural and tree planting design process and for feedback of sustainable projects to maximize particle removal capability.

1. Introduction

Particulate air pollution, especially the types with aerodynamic diameter of less than 2.5 μm ($PM_{2.5}$), is a matter of public concern, because it is known to exacerbate a wide range of respiratory and vascular illnesses (Brunekreef & Holgate, 2002). With the quick development of industrialization and urbanization in Chinese mega cities, particulate air pollution has rapidly increased (Chan & Yao, 2008). According to the statistical data calculated by the Beijing Municipal Environmental Monitoring Center (BJMEMC), 42 days in 2015 indicated serious $PM_{2.5}$ pollution, which accounted for 12% of the full year, and the average concentration of these heavily polluted days was over 280 μg/m^3 (BJMEMC, 2015). Residential districts are classified as places where people spend more than 40% of their time, and $PM_{2.5}$ in these places have certainly attracted considerable attention from citizens (Klepeis et al., 2001).

Under this circumstance, strategies on improving air quality in built environments have become more imminent than before. A universally accepted belief is that trees with large leaf area density and turbulent air movements created by their structure can capture particulate matters (Beckett, Freer-Smith, & Taylor, 1998). Recently, various studies have performed wind tunnel tests or field measurements to quantify deposition velocities or capture efficiency of different tree species, thereby estimating the consequences of urban landscape greening schemes of contrasting species composition (Freer-Smith, Beckett, & Taylor, 2005; Mori et al., 2015; Ould-Dada, 2002; Ould-Dada & Baghini, 2001). Some studies have showed that conifers have greater deposition velocity than deciduous trees by capturing 0.8 μm NaCl particles (Beckett, Freer-Smith, & Taylor, 2000a; Beckett, Freer-Smith, & Taylor, 2000b; Freer-Smith, Khatib-El, & Taylor, 2004). Small stems and large leaves were found to increase relative deposition velocity (Freer-Smith et al., 2004). Comparison of particulate deposition velocities on pine, yew and ivy showed that pine had the maximum capture ability (Przybysz, Sæbø, Hanslin, & Gawrońskia, 2014); and greater deposition velocities on needles than broadleaves were found in soot particles (Hwang, Yook, & Ahn, 2011). Juniper had larger deposition velocity in wind tunnel test than loblolly pine (*Pinus taeda*) (Lin, Katul, & Khlystov, 2012). Moreover, an experiment showed that coarse particles were more easily washed off from leaves during rain (Przybysz et al., 2014), and approximately 60% of the particle deposited on

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foliages was washed off with water, whereas the existing 40% was found in the wax layer of foliages (Popek, Gawrońska, Wrochna, Gawroński, & Sæbø, 2013). In addition, a field experiment revealed that particles smaller than 10 μm could not be washed off by water (Terzaghi et al., 2013). Sampling confirmed a positive correlation between particle deposition of hairy leaves and the wax layer of leaves (Sæbø et al., 2012). Full-scale field measurements performed by Salmond et al. (2013) showed that trees could accumulate pollutants in tree canyons; and tree canopy density, leaf area index, and air velocity were the most effective factors that affected the attenuation coefficient of $PM_{2.5}$ in street canyons (Jin, Guo, Wheeler, Kan, & Che, 2014).

Several numerical studies on the deposition effects of trees on particulates have found that trees act as solid barriers, and tree species, crown size, porosity and leaf area density, tree height and tree-building distance all affected particle dispersion (Gallagher et al., 2015). Ries and Eichhorn (2001) used a 2D tree model that considered tree permeability to analyze the influence of trees in street canyons. Gromke et al. (2008) compared the different tree crown porosities and stand densities in street canyons with FLUENT™. Buccolieri et al. (2011) modeled the tree-atmosphere interaction on PM_{10} in an actual junction with two different wind directions using FLUENT. The results showed that street-level gaseous pollutants essentially relied on wind direction and street canyon aspect ratio. Moreover, urban trees produced adverse effect on gaseous pollutant dispersion in street canyons resulting from the weakening pedestrian airflows by trees. Numerical comparisons on the effect of two conifer trees (i.e., pine and cypress) on particulate dispersion showed that cypress had greater deposition ability than pine (Ji & Zhao, 2014). Numerical simulations using CFD code OpenFOAM indicated that the annual average increase of PM_{10} and elemental carbon ranged from 0.2% to 2.6% and 1% to 13%, respectively, depending on vegetation types (Vranckx, Vos, Maiheu, & Janssen, 2015). Trees and grass deposition were finite with 2.8% reduction for trees and 0.6% for grass (Jeanjean, Monks, & Leigh, 2016); and lower wind velocity resulted in worst effects of trees on air pollutants deposition, whereas perpendicular winds led to larger pollution concentrations in street canyons in the presence of trees (Jeanjean, Buccolieri, Eddy, Monks, & Leigh, 2017). A WA CFD-RANS methodology estimating the NO_2 distribution in a real urban canopy showed that good correlation existed between model estimates and measurements, which made the pollutant concentration gradients reproduce in an actual urban district with a considerably high spatial resolution (Santiago et al., 2017). However, some modeling studies have described trees as a sink for turbulence without considering the deposition effect. Two numerical studies using ENVI-met indicated that trees can increase pollutant concentration in street canyons (Wania, Bruse, Blond, & Weber, 2012) and between different buildings (Vos, Maiheu, Vankerkom, & Janssen, 2013).

Considerable number of previous research has studied the behavior of air pollutant dispersion in different types of buildings ranging from isolated buildings or building arrays in urban environment. The methods used included full-scale field measurements, wind tunnel tests, and CFD simulations. A field experiment, which examined the fluctuating time series of particulate on the wall in a building complex, demonstrated that concentrations were significantly influenced by the ratio between the width and height of the building (Santos, Griffiths, Roberts, & Reis, 2005). Mfula, Kukadia, Griffiths, and Hall (2005) conducted a wind tunnel test with an assumed building model scale of 1:100 to investigate the location of influence of air pollution sources on magnitude and concentration dispersion. Similarly, two nominal wind tunnel scales of 1:1 and 1:200 were established to determine the pollutant dispersion around buildings (Lateb, Masson, Stathopoulos, & Bédard, 2010). Other numerical studies have shown that a wide street and low building height favor air ventilation and the removal of air pollutants in street canyons (Chan, Dong, Leung, Cheung, & Hung, 2002; Zhang, Gu, Lee, Fu, & Ho, 2011). Ng and Chau (2014) selected building permeability and setback as the building design elements to evaluate the effectiveness of different configurations that mitigate air pollutant in isolated canyons using RANS equations. Another simulation study on the influence of viaduct configurations and ground heating intensities on street particle dispersion within idealized street canyons showed that viaducts significantly reduce spatial averaged indoor concentrations of gaseous pollutant and the number of indoor particles (Hang et al., 2016).

With the above findings, several full-scale field experiments, wind tunnel tests, and simulation studies have been conducted to consider the effect of trees on particle dispersion in urban street canyons or assumed building complexes. However, full-scale field measurements are usually performed on a limited number of field points in space (Montazeri & Blocken, 2013). In addition, extraneous and uncontrolled wind and weather conditions resulted in repeating an experiment under identical conditions is impossible and time-consuming (Schatzmann & Leitl, 2011). Given the rapid development of computational technologies due to improvement in software and numerical modeling, CFD has been increasingly used and adopted to simulate airflow and pollutant dispersion around buildings (Wang & Mu, 2010). In addition, the CFD technique is certified as the preferred strategy (Britter & Schatzmann, 2007), which is appropriate for parametric studies for various physical airflow and dispersion processes at micro scale level (Gousseau, Blocken, Stathopoulos, & Van-Heijst, 2011).

Previous numerical studies have investigated the separate effects of buildings ranging from single building to building arrays, or trees, such as crown morphology, types and layout, or the combined effects of building morphology and trees on PM dispersion (Hofmana et al., 2016; Janhäll, 2015; Jeanjean et al., 2016; , 2017; Lateb et al., 2016; Xia, Niu, & Liu, 2014). However, few studies focus on the coupled influence of different building-tree arrangements. Furthermore, outdoor particle dispersion is expected to be variable because of the interactive relationship between building-tree arrangements under the context of built environments. On the standpoint of urban design, the pursuit of sustainability should be closely linked with coupled influences of building-tree arrangements on air pollutants. Urban planners would greatly benefit from the knowledge regarding the mechanisms behind the removal effect of PM using configurational combination of building and tree for optimizing complex arrangements. This study aims to highlight the need to simulate the aerodynamic and deposition effects of building-tree arrangements on $PM_{2.5}$ dispersion, in order to achieve scientific decision-making on optimal arrangements for a sustainable design in urban residential areas. Based on CFD approach, 12 typical building-tree arrangements were simulated using RANS and revised generalized drift flux models: 1) to quantify the aerodynamic and deposition effects of building-tree arrangements on outdoor $PM_{2.5}$ dispersion; and 2) to obtain the optimum building-tree arrangement via a series of simulations and comparisons.

2. Methodology

2.1. Computational approach

2.1.1. Airflow model

According to the recommendation of AIJ and COST 732 (Franke, Hellsten, Schlunzen, & Carissimo, 2011; Tominaga et al., 2008), the standard k-ε model was selected for airflow simulation. Vegetation was described as a porous-medium in the airflow model, considering the effect of vegetation canopy on airflows. Branches and trunks were approximated to leaves and canopy (Lin, Li, Zhu, & Qin, 2008). Thus, the main influence of vegetation on wind flow was the reduction of air velocity due to drag forces and pressure from an aerodynamic perspective. Consequently, vegetation effects on turbulent flow fields were modeled, including the drag forces in momentum equations. Turbulence production and accelerated turbulence dissipation within the canopy were accounted for the additional turbulence source terms. The details of these equations are as follows: