Science of the Total Environment 574 (2017) 569–582

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

A decision support tool for evaluating the air quality and wind comfort induced by different opening configurations for buildings in canyons

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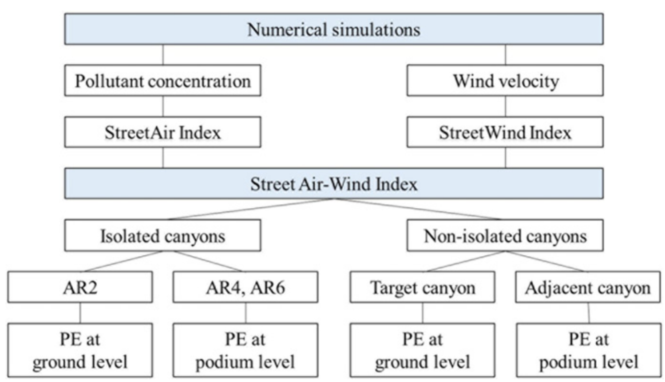
HIGHLIGHTS

- A new Street Air-Wind Index was formulated for evaluating both the air quality and wind comfort for pedestrians.
- Permeability value of 10% was adequate for improving the pedestrian environment inside street canyons.
- Building openings were not always effective in improving the air quality and wind comfort for non-isolated canyons.
- Specific types of opening configurations were suggested for planning and designing buildings inside urban streets.

GRAPHICAL ABSTRACT



Note: PE indicates permeable elements.

ARTICLE INFO

Article history:
Received 8 June 2016
Received in revised form 1 August 2016
Accepted 11 September 2016
Available online 14 October 2016

Keywords:
Street canyons
Building openings
Air quality
Wind comfort
Street Air-Wind Index

ABSTRACT

This study formulated a new index for evaluating both the air quality and wind comfort induced by building openings at the pedestrian level of street canyons. The air pollutant concentrations and wind velocities induced by building openings were predicted by a series of CFD simulations using ANSYS Fluent software based on standard k-ε model. The types of opening configurations investigated inside isolated and non-isolated canyons included separations, voids and permeable elements. It was found that openings with permeability values of 10% were adequate for improving the air quality and wind comfort conditions for pedestrians after considering the reduction in development floor areas. Openings were effective in improving the air quality in isolated canyons and different types of opening configurations were suggested for different street aspect ratios. On the contrary, openings were not always found effective for non-isolated canyons if there were pollutant sources in adjacent street canyons. As such, it would also be recommended introducing openings to adjacent canyons along with openings to the target canyons. The formulated index can help city planners and building designers to strike an optimal balance between air quality and wind comfort for pedestrians when designing and planning buildings inside urban streets and thus promoting urban environmental sustainability.

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http://dx.doi.org/10.1016/j.scitotenv.2016.09.083

1. Introduction

Rapid urbanization urges cities to continuously expand their boundaries, and makes urban fabric denser and taller. Closely packed high-rise buildings can develop urban sites to their maximum potentials (Rudlin and Falk, 2009). Despite so, the construction of buildings inevitably brings changes to the outdoor microclimate around building site. It may hinder the air movement within urban areas which subsequently affects outdoor wind comfort and air pollution dispersion (Yuan and Ng, 2012). The problem further aggravates in deep street canyons, where tall buildings are lining along narrow streets with considerable amount of airborne pollutants being emitted by vehicles (Park et al., 2004; Vardoulakis et al., 2003). The effects on outdoor air quality and wind comfort depend on the shape, size and orientation of a building as well as its interaction with the surrounding buildings. Low wind velocity leads to uncomfortable conditions and insufficient removal of traffic exhaust gases while high wind velocity leads to uncomfortable or even dangerous conditions for pedestrians (Jan, 2012). Wind discomfort will be experienced by pedestrians when the mean wind velocity is below 1 m/s (Ng and Tsou, 2005), or above 5 m/s (Janssen et al., 2013), whereas wind danger will be encountered when the mean wind velocity is above 15 m/s (Stathopoulos, 2009). Discomfort and dangerous conditions may be induced by strong winds near buildings (Iqbal and Chan, 2016; Tsang et al., 2012) which in turn may be caused by some types of building or street configurations, e.g. high-rise buildings or narrow street canyons (Reiter, 2010).

To mitigate these problems, numerous urban planning strategies have been proposed and investigated to alter urban morphologies and building configurations. Strategies including round shaped city forms (Hang et al., 2009), low building packing and frontal area densities (Buccolieri et al., 2010; Di Sabatino et al., 2007), low street aspect ratios (AR) (Baratian-Ghorghi and Kaye, 2013) and non-uniform building heights (Hang et al., 2012b) were proposed to increase ventilation rate and breathability of a city neighborhood (Hang et al., 2012a). However, these strategies appeal to be less attractive in urban areas as they lead to a significant loss in valuable development floor areas (Pal et al., 2013). Accordingly, it calls for development of new passive architectural design and urban planning concepts that can enhance ventilation, improve air quality and wind comfort for pedestrians without sacrificing substantial amount of usable floor area.

Quite often, this problem was attempted to be resolved by increasing the permeability of buildings. Building openings, including separations, voids, permeable elements and sky gardens, have been proposed in a number of previous studies (Yao, 2002; Yuan and Ng, 2012; Yuan et al., 2014). Some of them have also been incorporated into city or country planning policies, e.g. Sustainable Building Guidelines in Hong Kong (HKBD, 2011), Residential Design Codes in Western Australia (State of Western Australia, 2015) and Tall Building Design Guidelines in Toronto (Toronto City Council, 2013). Openings can accelerate the wind velocity in street canyons by enhancing convection and diffusion processes (Yuan and Ng, 2012). High wind velocity could enhance pollutant dispersion process leading to lower pollutant concentrations (Yuan et al., 2014). Sky gardens could increase the ventilation efficiency in street canyons by up to 43% (Yao, 2002), while stepped podium or openings at the ground level could improve the pedestrian-level wind environment by reducing the relative frequency of stagnant ventilation conditions by 62%–90% (Yuan and Ng, 2012). However, wind conditions in openings within buildings and gaps between buildings are often considered to be less desirable due to the occurrence of pressure short-circuiting between windward and leeward facade (Blocken and Carmeliet, 2004).

Conceivably, openings of different sizes at different locations may produce different effects on the wind conditions and air quality at pedestrian level, since their aerodynamic geometries may cause strong winds to be accelerated at pedestrian level (Stathopoulos, 2009). Previously, mean wind velocity ratio and normalized pollutant concentration were two simple indicators used for evaluating the ambient wind environment and air quality respectively (Hu and Yoshie, 2013). Besides, indices intended for evaluating ventilation efficiency, like purging flow rate, residence time and visitation frequency, which were originally developed for evaluating indoor environments, have also been successfully extended to outdoor areas (Bady et al., 2008). However, such indices were mainly focused on discrete points or spatial-averaged values rather than variations in different spatial locations (Razak et al., 2013). This might lead to unacceptable assessment results, and is particularly not useful for wind comfort assessment as both high and low velocities are not desirable for human beings.

Worse still, specific requirements on wind comfort and air quality have always been considered in isolation. Wind comfort, here referred to effects of wind on people ranging from the feeling of a light breeze on the skin to being blown over by a strong gale, was mainly investigated along with thermal comfort in most pedestrian wind assessment studies (Blocken and Carmeliet, 2004; Soligo et al., 1998). Also, a majority of research findings on wind comfort or air quality were presented in contours which made urban planners and building designers difficult to interpret and use during urban planning and building design process. In view of this, it urgently calls for the development of a practical evaluation tool that can integrate the assessment of both air quality and wind comfort in different spatial locations for aiding urban planners and building designers in comparing different building designs along urban streets.

Besides, a majority of these investigations were confined to isolated street canyons with a single pollutant source without taking into consideration the influences of other pollutant sources from adjacent canyons. High wind velocity could remove pollutants out of the canyon with pollutant sources (target canyon) to adjacent canyons, which improved the air quality inside the target canyon while simultaneously worsened the air quality inside adjacent canyons. Given that building openings can enhance mass transport process in isolated street canyons (Hang et al., 2011), it is of particular interest to reveal whether similar effects also occur in non-isolated canyons with multiple pollutant sources.

Accordingly, the objectives of the present paper are fourfold. It aims: (i) to develop a tool for simultaneously evaluating the air quality and wind comfort at pedestrian level; (ii) to demonstrate the application of the evaluation tool in numerical simulations; (iii) to investigate the effects of building openings on the air quality and wind comfort at the pedestrian level inside both isolated and non-isolated canyons; and (iv) to identify the best opening configurations in buildings that can strike an optimal balance between air quality and wind comfort.

2. Methodology

To facilitate the investigations, building models with specific type of opening configurations were studied through computational fluid dynamics (CFD) simulations. The wind velocity and air pollutant concentration data obtained from the CFD simulations were subsequently input into a newly proposed Street Air-Wind Index so as to evaluate the effect of building openings on the air quality and wind comfort at the pedestrian level inside street canyons. Three scenarios were modeled and studied to compute the Street Air-Wind Index values for both isolated and non-isolated canyons in the following context.

2.1. Description of CFD modeling

2.1.1. Physical models

Scenario I simulates the situation that composes of two identical building blocks without or with openings. Three-dimensional (3D) isolated urban canyon models consisting of two building blocks with corresponding canyon width of 18 m, length of 180 m and three different street aspect ratios (i.e. AR2, AR4, and AR6, where AR is defined as building height (H)/street width (W)) were constructed initially. As shown