Atmospheric Environment 164 (2017) 85–101

Contents lists available at ScienceDirect

Atmospheric Environment

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

# An investigation on the effect of street morphology to ambient air quality using six real-world cases

Jialei Shen, Zhi Gao*, Wowo Ding, Ying Yu

*School of Architecture and Urban Planning, Nanjing University, 22 Hankou Road, Nanjing, Jiangsu Province, 210093, China*

## HIGHLIGHTS

- Relationship of street morphology and air quality for 6 real-world cases is analyzed.
- Street continuity ratio and other indices are proposed to quantify street morphology.
- Air quality improved with a decreasing aspect ratio due to larger vertical exchange.
- Higher street continuity and spatial closure lead to a stronger channel flow.
- Octagon and oblique intersections are favorable for central street ventilation.

## ARTICLE INFO

*Article history:*
Received 14 April 2017
Received in revised form
25 May 2017
Accepted 26 May 2017
Available online 29 May 2017

*Keywords:*
Street morphology
Urban form
Street ventilation
Pollutant dispersion
Air quality
CFD simulation

## ABSTRACT

Street canyons are vulnerable to air pollution mainly caused by vehicle emissions, which are therefore closely related to pedestrians' health. Previous studies have showed that air quality in street canyons is associated with street morphology, though the majority of them have focused on idealized street models. This paper attempts to investigate the relationship of street morphology to air quality for 6 irregular real-world cases selected from America, Europe, and China, i.e. Manhattan, Paris, Barcelona, Berlin, London and Nanjing. Each street is analyzed as a set of slices to propose a couple of morphology indices for quantitatively assessing the actual street morphology. Pollutant transport rate of mean flows and turbulent diffusion, net escape velocity and age of air are obtained from computational fluid dynamics (CFD) simulations to assess the ventilations and pollutant dispersion within street canyons with a parallel approaching wind. The results show that the street morphology characteristics, including the street width, lateral openings and intersections, are closely related to the air flows in street canyons. The air quality improves with a decreasing aspect ratio of central street owing to a larger vertical exchange through the street roof, which suggests an open central street is of better air quality. The lateral openings and intersections of streets have important effects on the air flows in street canyons, and the effects are particularly pronounced when the street widths are similar. The street continuity ratio indicates street continuity. It relates to the openings and the symmetry of a street and impacts on the air flows and pollutant dispersion through the lateral openings of the central street. The street spatial closure ratio is determined by the street continuity ratio and the aspect ratio of the central street. When the aspect ratio of central street is not excessively high, higher values of street continuity ratio and spatial closure ratio can lead to a stronger channel flow in street canyons and improve the air quality. The octagon intersections are favorable for air flowing through the lateral openings and improve the channel flows. The oblique intersections can also greatly improve the street ventilations, mainly due to the enhanced air flows through the lateral openings and the increased turbulent diffusion through the street roofs.

## 1. Introduction

The past few decades have seen urbanization as a global phenomenon featuring explosive urban expansion and increasing building density with emerging high-density compact urban forms. One of the major problems in urban areas is air pollution (Kastner-Klein et al., 2004; Tominaga and Stathopoulos, 2013), particularly for some developing countries like China. Vehicle emission is

---

* Corresponding author.
*E-mail address:* zhgao@nju.edu.cn (Z. Gao).

http://dx.doi.org/10.1016/j.atmosenv.2017.05.047
1352-2310/

usually the major pollutant source in urban areas (Britter and Hanna, 2003; Liu et al., 2005). High-density compact urban forms affect flow patterns in urban canopy, causing further pollutant accumulation and poor air quality (Buccolieri et al., 2010).

Previous investigations have studied the relationship of urban form to air quality. Hang et al. analyzed the influence of overall city forms, street orientations, street configurations (Hang et al., 2009a, 2009b, 2009c), and building height variability (Hang et al., 2012b; Lin et al., 2014) on urban ventilations and pollutant dispersion in idealized urban models with computational fluid dynamics (CFD) simulations and wind tunnel experiments. Buccolieri and Di Sabatino et al. studied pollutant dispersion and city breathability in idealized compact urban areas with different packing densities and wind directions (Di Sabatino et al., 2007; Buccolieri et al., 2010, 2015). Particularly, numerous investigations have studied pollutant dispersion and air quality in street-scale models, since the majority of vehicle emissions occur in urban street canyons (Moonen et al., 2011). Investigators have conducted CFD simulations and wind tunnel experiments to study air flows and pollutant dispersion affected by street morphology, which included the aspect ratio (e.g. Oke, 1988; Sini et al., 1996; Chan et al., 2001, 2002; Chang and Meroney, 2003; Ahmad et al., 2005; Liu et al., 2005, 2011; Li et al., 2005, 2006, 2009; Solazzo and Britter, 2007; Cheng et al., 2008; Salim et al., 2011), building configurations (e.g. Kastner-Klein and Plate, 1999; Kastner-Klein et al., 2004; Huang et al., 2000; Xia and Leung, 2001; Xie et al., 2005; Nazridoust and Ahmadi, 2006; Huang et al., 2015), and vegetation in street canyons (e.g. Gromke and Ruck, 2007; Gromke et al., 2008; Buccolieri et al., 2009, 2011). Hang et al. studied street ventilations in high-rise long street models (Hang et al., 2010, 2012a). Gu et al. (2011) analyzed the effect of uneven building layout on flow patterns and pollutant dispersion in non-uniform street canyons. Ramponi et al. (2015) presented CFD simulations of ventilations for generic configurations with parallel streets of equal and unequal widths.

An actual street is of complex morphology characteristics and it is difficult to fully study all the details. Therefore, most previous studies on street ventilations have investigated street canyons with idealized geometries. Only a few investigations have considered urban areas or streets in their various actual states. Xie and Castro (2009) and Xie et al. (2013) investigated air flows and pollutant dispersion in an actual urban area (i.e. the DAPPLE site in central London) with large eddy simulation (LES) and wind tunnel experiments. Panagiotou et al. (2013) investigated city breathability and its spatial variations in the DAPPLE site with CFD simulations based on Reynolds-averaged Navier-Stokes (RANS) equations. Tominaga (2012) investigated city breathability in an irregular actual urban area of Niigata City by means of CFD simulations. Blocken et al. studied pollutant dispersion, wind environment and microclimate of downtown Montreal, Eindhoven University campus and Rotterdam (Gousseau et al., 2011; Blocken et al., 2012; Janssen et al., 2013; Toparlar et al., 2015). Thaker and Gokhale (2016) investigated the effect of different urban traffic-flow patterns on pollutant dispersion in different winds with CFD simulations in a real asymmetric street canyon located in the center of Guwahati, India. These investigations mainly focused on specific actual urban areas but rarely quantified actual urban morphology to facilitate further applications to more cities.

Few of previous studies have investigated street ventilations in models with different actual street morphology characteristics. However, some detailed morphology characteristics of real scenarios can have significant impacts on local flow patterns, which thus deserve more quantitative investigations. Besides, many cities are too irregular in urban morphology to be represented by idealized geometric models. This paper quantitatively investigates the influences of detailed street morphology on the street ventilations and pollutant dispersion for better understanding flow patterns in street canyons with irregular actual geometric models. Six real-world street cases with different morphology characteristics, i.e. Manhattan, Paris, Barcelona, Berlin, London and Nanjing, are studied. A parallel approaching wind is investigated owing to its significant effects on pollutant dispersion in street canyons with the existence of channel flows, which is an important phenomenon widely studied (e.g. Buccolieri et al., 2010; Gu et al., 2011; Hang and Li, 2011; Hang et al., 2012a, 2012b). In addition, street intersections strongly impact upon the pollutant concentrations in urban canopy (Soulhac et al., 2009). This paper analyzes the flow patterns at typical street intersections of actual streets, e.g. the orthogonal intersections, oblique intersections and octagon intersections, which have not been widely investigated in previous literatures.

In this paper, both street morphology and street ventilations of six real-world cases are quantitatively analyzed. Some morphology indices are proposed to quantify street morphology, e.g. street continuity ratio and street spatial closure ratio. Street ventilations and pollutant dispersion are indicated by net escape velocity, exchange velocity and age of air obtained from CFD simulations. Mean flows and turbulent diffusion through the street roof, leeward and lateral openings of each case are analyzed. The results may be meaningful for urban design, since some morphology characteristics analyzed in this paper prove to be favorable for street ventilations and pollutant dispersion.

## 2. Street morphology analysis

Six distinctive cities of America, Europe, and China are investigated in this paper, i.e. Manhattan, Paris, Barcelona, Berlin, London and Nanjing (Fig. 1). The building heights in these cities are relatively uniform, particularly in the European cities (Buccolieri et al., 2015). Buildings with 6 stories are very common in these cities (Hu and Yoshie, 2013). The investigated streets, which are located in the center of each city, have representative morphology characteristics of the city (e.g. the street width, intersections, and lateral openings) (Ding and Tong, 2011).

The street configurations of the 6 cases are illustrated in Fig. 2. The spaces that are disconnected with street canyons, e.g. the isolated courtyards, are not considered, as the present research focuses on the air flows and pollutant dispersion in street canyons. Similar simplifications of street configurations could be found in previous literatures (e.g. Panagiotou et al., 2013). Each street area is 120 m wide (in x axis) and 612 m long (in y axis). The building height variations are not considered, since the present investigation mainly focuses on the planar morphology characteristics of different cities. Buildings with 6 stories are common in the investigated cities, thus all the buildings are unified into 18 m high, assuming that each story is 3 m high. Each street case has one central main street intersecting with several secondary streets. The central street is a key area to be investigated as located in the middle of the street area. The central axis is located in the center of the street area, which divides the entire street area into two identical sections regardless of the lateral buildings.

Each street case has typically different morphology characteristics, which are difficult to quantitatively characterize due to the irregularities of street configurations, especially the ones represented by Nanjing. However, a method termed street slice analysis does show an advantage to quantitatively assess street morphology that processes the continuous street space into a series of separated slices with an equal interval. All these slices are perpendicular to the central axis of street and can be divided into 3 types according to the presence of buildings, as shown in Fig. 3(a): street slices with buildings on both sides (non-open), street slices with buildings on one side (single-side-open), and street slices with no building