ARTICLE IN PRESS

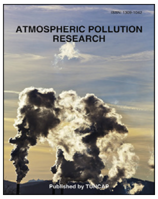
Atmospheric Pollution Research xxx (2016) 1–12

HOSTED BY

Contents lists available at ScienceDirect

Atmospheric Pollution Research

journal homepage: http://www.journals.elsevier.com/locate/apr



Effects of low boundary walls under dynamic inflow on flow field and pollutant dispersion in an idealized street canyon

Le Wang, Qiang Pan, Xi-Peng Zheng, Shun-Sheng Yang*

Southwest Jiaotong University, School of Civil Engineering, Chengdu, PR China

ARTICLE INFO

Article history:
Received 22 September 2016
Received in revised form
7 December 2016
Accepted 7 December 2016
Available online xxx

Keywords:
Idealized street canyon
Pollutant dispersion
Dynamic conditions
Low boundary walls
Numerical simulation

ABSTRACT

In this study, we examine the magnitude of the boundary layer inflow that gradually changes with time at the top of a building. A standard k-ε model was used to study how low boundary walls (LBWs) under dynamic wind field and dynamic vehicle flow affect the dispersion of pollutants in an idealized street canyon. The results show that the flow field under dynamic inflow inside the idealized street canyon within LBWs is composed of a major eddy and three corner eddies at the street level. When the external wind speed drops, the air is expanded, regarding which the canyon from air expansion is approximately 11 m high at time t = 25 min and 3 m at time t = 33 min. The air at the road corners is correspondingly expanded. The presence of LBWs increases the peak of pollutant concentrations in the canyon and alters the pollutant distribution at the canyon bottom under the dynamic flow at different time points. In the LBWs street canyon compared with the non-LBWs street canyon, the pollutant concentration peaks at time t = 25, 29, and 33 min increase by 12.74%, 30.90% and 22.80%, respectively. The presence of LBWs significantly decreases the maximum *x*-direction wind speeds at 1-m height in the bottom canyon at different time points but alters the wind directions at the corners and changes the value and distribution of turbulent kinetic energy in the canyon. The largest leeward and windward y-direction wind speeds under dynamic inflow are 27.41% and 32.75% compared with under steady inflow.

1. Introduction

Urban street air pollution in China has become increasingly severe following the rapid increase of the number of vehicles and the growth of the urban population. The pollutant dispersion in a street canyon is affected by greening and noise reduction measures such as noise barriers, low boundary walls (Mcnabola et al., 2009) and vegetation.

Early studies regarding street canyons focused on how pollutant dispersion was affected by the asymmetry heterogeneity of street canyons (Hoydysh and Dabberdt, 1988; Venegas and Mazzeo, 2000; Gu et al., 2011; Schatzmann et al., 2000) and the thermal effect (Xie et al., 2005; Uehara et al., 2000) under the condition of steady inflow. In recent years, the effects of barriers (e.g., LBWs, noise barriers, parked cars, and vegetation) on pollutant distribution in streets have been gradually simulated (King et al., 2009; Finn et al., 2010; Gallagher et al., 2013; Salmond et al., 2013; Tiwary and Kumar, 2014; Gallagher et al., 2015). The effects of different vegetation-related factors on pollutant distribution in street canyons were mainly studied through numerical simulation or wind tunnel tests (Balczó et al., 2009; Efron and Petrosian, 2015; Buccolieri et al., 2009; Vos et al., 2013). It was found that the presence of vegetation and trees weakened the convective diffusion of pollutants to certain extents and led to the increase of pollutant concentrations in street canyons (Li et al., 2013). Gromke (2011), Gromke and Ruck (2007, 2009, 2012), Gromke et al. (2008) characterized the flow field and pollutant distribution and analyzed the effects of inflow direction, porosity, and inflow speed on pollutant distribution in a street canyon with the presence of trees by replacing trees with a porous medium and through experiments and simulation. A large-eddy simulation (LES) model was used to simulate a street canyon with parked cars and to investigate how the presence and layout of parked cars would protect passers-by (Gallagher et al., 2011).

Some researchers simulated or experimentally measured how solid barriers, including noise barriers (Ning et al., 2010; Baldauf et al., 2008, 2016) and LBWs (Gallagher et al., 2012; Schulte et al.,

---

* Corresponding author.
E-mail address: seanse@126.com (S.-S. Yang).
Peer review under responsibility of Turkish National Committee for Air Pollution Research and Control.

http://dx.doi.org/10.1016/j.apr.2016.12.004

Please cite this article in press as: Wang, L., et al., Effects of low boundary walls under dynamic inflow on flow field and pollutant dispersion in an idealized street canyon, Atmospheric Pollution Research (2016), http://dx.doi.org/10.1016/j.apr.2016.12.004

2014; Steffens et al., 2013), would improve air quality on open streets, urban streets, and highways. In numerical simulation studies, the LBWs can act as baffle plates, which redirect the flow and thereby affect the dispersion in the street canyon (Gromke et al., 2016). A combined monitoring and numerical modeling study was carried out to highlight the role of an existing LBW in an urban street in Dublin, Ireland (Mcnabola et al., 2008). In comparison between LBW and other passive control measures, the numerical simulations showed that LBW at the central bottom outperformed the hedgerows in improving the air quality in most parts of the canyon (Gromke et al., 2016). The LBW affects the pollutants in a street canyon differently depending on the wind direction. When the wind direction is parallel to the street canyon, the presence of LBWs will reduce the roadside pollutant concentrations at the height of passers-by (Mcnabola et al., 2009). The presence of LBWs would lead to the increase or decrease of the leeward and windward pavement pollutant concentrations, depending on the building aspect ratio (Gallagher et al., 2012). The joint effect of noise barrier and plants was also studied. Tong et al. (2015) simulated the effects of six conceptual roadside vegetation/solid barrier configurations on near-road size-resolved particle concentrations.

Experiments showed that there was a time-variable wind field above the street canyon and that, specifically, velocity and velocity direction changed all the time (Hahn et al., 2009; Zhang et al., 2011; Murena and Mele, 2014). There are limited studies that consider the wind flow in a street canyon as a dynamic wind field due to the difficulty that the velocity direction can be hardly modeled under the boundary conditions adopted by the existing commercial software. Zhang et al. (2011) proposed a boundary pattern for numerical simulation of the real wind field in a street canyon and found that a real wind field can cause air compression or expansion that facilitates pollutant spread. Murena and Mele (2014) used a k-ω SST turbulence model to numerically simulate a 2D street canyon by considering the time-dependent change of velocity; they found that the shape and position of vortices inside the street canyon were time dependent.

Generally, studies regarding barriers in street canyons are focused on the condition of steady inflow, especially with the presence of LBWs. Limited studies are in regards to the flow fields and pollutant distribution in idealized street canyons under real inflow or traffic flow. The effects of inflow, turbulent kinetic energy (TKE), and traffic flow on pollutant distribution in an idealized street canyon with LBWs have not been fully investigated. Therefore, in this study, through comparison between simulations and wind tunnel tests, we aim to study the wind fields and pollutant dispersion in an idealized street canyon with LBWs, under the dynamic changes of wind speed and pollution sources (vehicle flow) within a certain period of time. Numerical simulations are performed using the CFD commercial code ANSYS Fluent (ANSYS, 2009). The dynamic changes of speed entrance boundaries, TKE, the dissipation rate of TKE, and the pollutant source are realized via user-defined programming. This study is significant in investigating how LBWs under changing wind speed and vehicle flow would affect the flow field and the pollutant distribution in an idealized street canyon.

2. Methodology

2.1. Geometry and computational domain

The model of an idealized street canyon with LBWs is shown in Fig. 1. Because the wind direction is perpendicular to the street canyon, the structure of the canyon can be simplified as two-dimensional. Initially, a model of a generic idealized street canyon (20 m wide and 20 m high; height to width ratio = 1.0) was created. LBWs A and B (both 2-m-high, 0.1-m-wide) were set at the canyon bottom, 2 m away from the roadside buildings (Fig. 1a). The fluid domain sizes are 60 m (x-direction) × 100 m (y-direction). The inside of the street canyon was structurally divided into uniform grids. The grid size was $\Delta x = \Delta y = 1/200H = 0.1$ m, and the size of the near-wall first layer was 0.1 m (Fig. 1c). The mesh of the upper part of the canyon was divided into structured grids (gradient rate = 1.01). Because of the dimensionless wall distance y^+ being more than 30, standard all functions (SWF) were applied for near wall treatment (ANSYS, 2009).

Four numerical simulations were conducted with different numbers of structured cells (10592, 48380, 132360, 354240) to find the grid-independent solution (see Subsection 3.1); a total of 132360 cells were chosen for computational modeling (Fig. 1b).

2.2. Data acquisition and boundary conditions

The main objectives of this study are to investigate how dynamic wind speed and vehicle flow would affect the wind field and pollutant dispersion in a street canyon with LBWs. The dynamic wind speed was defined as the inflow perpendicular to the entrance and with time-variable speed. In our simulation, we used the measurement data of wind speed and vehicle flow as the inlet boundary and pollutant source, respectively.

An anemometer was used to measure the wind speed under a real environment. The anemometer recorded every 2 min and the record was the average wind speed within 2 min. The sampling site was located at the top of a building (100 m high above the ground) and the sampling time was from 16:00 to 17:00. The variations of wind speed and vehicle flows are shown in Fig. 2. Evidently, the wind speed changed rapidly during the observation period in an obviously pulsatory way, without any regularity. Moreover, the vehicle flows at 7:00–8:00 in the Jiaoda segment on Xingqing Road, Xi'an City were monitored. The total number of vehicles every 2 min was counted, which was converted to the average vehicle flow per hour and thus used to estimate the carbon monoxide (CO) emission factor. The vehicle flow maximized at approximately 7:20 and then declined in a pulsatory way. Note that the observations here were made only to reflect the real changes of wind speed and vehicle flow, i.e., we did not consider the effects of sampling time or site.

During the simulation, we supposed the pollution gas was emitted from a linear source. The CO emission factor of vehicles was determined from the changes of vehicle flow. Because the vehicle data were measured in China and to make it more practical, we adopted the findings of Chinese scholars to estimate the CO emission factor as follows (Cheng et al., 2009):

$$S = E_{co}Q/3600 \tag{1}$$

where S is the pollutant source intensity of vehicle emission in mg/(s·m); Q is the vehicle flow in the street per hour. The comprehensive emission factor E_{co} of vehicles is computed as follows:

$$E_{co} = 42.531V^{-0.1185} \tag{2}$$

where V is the average vehicle driving speed, km/h. Combining real road observation and vehicle speed limits, we set $V = 40$ km/h (Gromke and Ruck, 2007).

Because the CO emission limit values of gasoline passenger vehicles in China are inconsistent among different time periods (Huo et al., 2015), we adopted the correction pollutant source Eq. (3), which improved the applicability of Eq. (1). The correction pollutant source equation was computed as follows:

Please cite this article in press as: Wang, L., et al., Effects of low boundary walls under dynamic inflow on flow field and pollutant dispersion in an idealized street canyon, Atmospheric Pollution Research (2016), http://dx.doi.org/10.1016/j.apr.2016.12.004