J. Wind Eng. Ind. Aerodyn. 99 (2011) 46–58

Contents lists available at ScienceDirect

Journal of Wind Engineering and Industrial Aerodynamics

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

Pollution removal effectiveness of the pedestrian ventilation system

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ARTICLE INFO

Article history:
Received 16 March 2010
Received in revised form
17 September 2010
Accepted 22 October 2010
Available online 20 November 2010

Keywords:
Pollution
Street canyon
Air exchange rate
Heat island
Urban design
Sustainable street air quality
Modeling
Pedestrians' comfort

ABSTRACT

Dispersion of vehicular pollution through street canyons has been widely studied in order to find strategies for reducing concentration level. Recently, a pedestrian ventilation system (PVS), an active mitigation strategy, has been proposed to enhance pedestrian comfort indices and to induce appropriate air movement. This paper investigates the performance of PVS to control pollution dispersion within street canyons. Pollution control is achieved by exhausting/supplying air from/to the street canyon through the PVS. In the present paper, the effectiveness of these strategies was studied by varying the parameters that affect dispersion, such as aspect ratios (AR) and thermal stratifications.

Computational Fluid Dynamics (CFD) has been selected as the investigation tool. Prior to simulations, the proposed model was successfully validated using two sets of experimental data. Four case-studies were also used to investigate the aspect ratio and the stratification effect. These test cases were developed based on small scale studies in a wind tunnel. Results show the ability of the PVS to change the airflow pattern through the street canyon, resulting in significant pollution removal, especially from the pedestrian level. Moreover, the air and pollution exchange rate concepts have been used for better evaluation of the PVS performance. Furthermore, a breakthrough index was proposed to evaluate the effect of the PVS airflow rate.

1. Introduction

Industrialization has imposed new challenges on modern cities. Among them, the increase of air pollution within the inhabited environment is a serious problem in the present century. Recently, the hazardous air quality at the pedestrian level has been reported in many big cities (e.g., New York, Hong Kong, and Tehran). The air quality can be even worse during Urban Heat Island (UHI) episodes; the temperature increase has both direct and indirect effects on elevating pollution concentrations inside street canyons. It directly raises the chemical reaction rate of the pollution in the street canyons. On the other hand, the flow regime can be significantly changed and intensified by the temperature difference between urban surfaces. As a result, the pollution transport can be strongly affected by this temperature difference as an indirect effect (Murena et al., 2009). The source input rate, the advection–diffusion inside and the transfer rate at the roof level of a canyon are known as three contributing mechanisms on the pollution removal inside the street canyons (Caton et al., 2003). It is also believed that the street canyon structure plays an important role in changing the flow regime and accumulation of pollution inside street canyons. Therefore, it is important to first understand the nature of the airflow pattern and contributed parameters.

Oke (1988) reported that the flow pattern depends on the canyon street aspect ratio (the ratio of the windward building's height to the canyon breadth; H/W), and categorized three flow regimes when the perpendicular wind speed over the street canyon is above 1.5 m/s: (a) isolated roughness flow (IRF), (b) wake interference flow (WIF), and (c) skimming flow (SF). In isolated roughness flow ($H/W<0.3$), buildings are considered as aerodynamic roughness, since in this regime, the flow travels a sufficient distance downwind the first building before encountering the subsequent building. On the contrary, in WIF, the wake region after the building encounters the next building as an obstacle in higher aspect ratios ($H/W<0.7$). In the third regime, a single circulation is produced inside the street canyon because of the skimming flow passing over the buildings where $0.7<H/W$. The strength of this circulation depends on the prevailing wind speed. A minimum of air exchange rate and pollution removal from the street canyon is reported in skimming flow (Hunter et al., 1992). Therefore, this flow has been extensively investigated and addressed in the literature of street canyon studies.

Pollutant exchange in street canyons is a function of vertical and horizontal air exchange from top-canopy and lateral surfaces. Many studies have been carried out to find the effect of the street canyon's character on the number, strength, circulation direction, and form of the circulation/circulations; street canyon aspect ratio (Murena et al., 2009), roof slope and shape (Rafailidis, 1997), street layout (Xie et al., 2006), ground and façade heating and atmospheric stability (Sini et al., 1996), street canyon configuration and type (step-up/down) (Chan et al., 2001), surface material (Oliveira Panao et al., 2009), and vegetation and tree planting (Gromke et al., 2008).

For example, a threshold aspect ratio of $1.60<H/W<2.67$ is suggested for increasing from a one-circulation regime to a two

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doi:10.1016/j.jweia.2010.10.007

counter-rotating circulation regime (Jeong and Andrews, 2002), where the main circulation is generally moved to the upper part of the street canyon, and a secondary weak circulation is observed in the bottom part. This threshold is reported to be $H/W=3.4-3.6$ for the evolution of the flow to a three-circulation regime in the street canyon (Kim and Baik, 2001).

The above mentioned investigations emerge the significance of street canyon characteristics on flow regime and pollution dispersion. However, there is still an urgent need for a comprehensive and reliable design guideline for pedestrian air quality. This means that many simplifications and limitations within the street canyon studies provide only preliminarily information for the urban planner and building designer to enhance the pedestrian air quality (Tominaga et al., 2008).

The modeling limitations include non-homogeneity in the shape and the material of buildings, discrepancy in providing boundary conditions, and ignoring details of stationary and mobile objects inside the street canyons (Mirzaei and Haghighat, 2010a). In addition to these limitations, the cities' landscapes are mostly developed and applying the outcome of such studies on existing street canyons is economically impractical. Moreover, even after applying these strategies such as the use of vegetation and higher-albedo materials, achieving appropriate pedestrian comfort is not guaranteed. For example, it is expected that tree planting always has a beneficial effect on outdoor air quality. However, this can influence the natural airflow regime of the street canyon; directly by creating a drag effect and indirectly by the alteration of surface temperatures. Moreover, the possibility of obtaining air circulation due to changing the facade temperature is expected inside the street canyon when higher-albedo materials are used.

Generally, the existing limitation in pollution removal from street canyons can be summarized in the weakness of these strategies in having active control on pedestrian comfort indices (i.e., air velocity, temperature, humidity, radiation, and pollution concentration). Recently, a pedestrian ventilation system (PVS), an active system, has been proposed by authors to improve the street canyon air quality: its ability to have a significant effect on the airflow pattern when the street canyon is under stable and unstable condition has been examined (Mirzaei and Haghighat, 2010b).

The present paper reports the performance of the PVS on removing pollution in a symmetric street canyon with a different aspect ratio and stability condition using Computational Fluid Dynamics (CFD).

2. Pedestrian ventilation system

The PVS controls the air exchange rate inside the street canyons by balancing turbulence and buoyancy with an adjustable source of mechanical turbulence (Mirzaei and Haghighat, 2010b). Illustrated in Fig. 1, the PVS guides air through a vertical duct going from the roof of the building to the pedestrian ventilation zone (PVZ) using ventilation ducts. The PVZ volume is extended around the region in which pedestrian activities occur. Also, different PVS strategies have been configured by installing two similar systems on adjacent buildings of the street canyon (Fig. 1); (A) exhausting strategy, (B) supplying strategy, and (C and D) washing flow strategies.

3. Methodology

3.1. Computational model

The Navier–Stokes (NS) equation was applied as the governing equation to study the performance of the PVS in removing pollution from the street canyon under different weather stabilities and aspect ratios. The conservation of mass is as follows:

$$\frac{\partial \overline{U}_i}{\partial x_i}=0 \tag{1}$$

and conservation of momentum

$$\overline{U}_j\frac{\partial \overline{U}_i}{\partial x_j}=-\frac{1}{\rho}\frac{\partial \overline{P}}{\partial x_i}+g\delta_{i3}-\frac{\partial}{\partial x_j}(\overline{u_i u_j})+\nu\frac{\partial}{\partial x_j}\left(\frac{\partial \overline{U}_i}{\partial x_j}\right) \tag{2}$$

where ρ is density, ν is kinematic viscosity, δ_{ij} is the Kronecker delta, g is the gravitational acceleration, $\overline{P}$ is mean pressure, $\overline{U}_i$ and u_i are mean and fluctuation parts of velocity. CFD approach was also used to solve governing equations. The standard k–ε was employed as turbulent model. The set of equations was solved using the commercial software FLUENT (Fluent, 2008).

3.2. Computational domain

In the present study, the length of the street canyon was assumed to be infinitely long to simplify from a three-dimensional domain to a two-dimensional frame (Meroney et al., 1996). Depicted in Fig. 2, five identical street canyons were assumed in the computational domain (AR=1; $H=W=100$ mm and AR=2; $H/2=W=100$ mm). The street canyon studied was the third one beyond the inflow boundary. A pollution source and two PVS on adjacent leeward and windward walls were set in this street canyon. The domain height size was considered to be $7H$ to model the buoyancy effect (Mirzaei and Haghighat, 2010b). Also, the lengths of the domain before and after the street canyon in which the PVS was installed were, respectively, $8H$ and $9H$. Using this technique, a periodic velocity profile over all street canyons was obtained. Domains of study were meshed with structured rectangular elements using GAMBIT software (GAMBIT, 2008). Trial runs with different maximum area for the meshes (i.e. 10 mm × 10 mm, 5 mm × 5 mm, and 2.5 mm × 2.5 mm) were preformed to ensure that the CFD model is independent from mesh size. To determine the gradient of velocity and pollution concentration, in the studied domain, a very fine mesh was considered close to the walls and ground in order to apply an enhanced wall treatment scheme. The maximum and minimum areas of the meshes were, respectively, 25 and 0.085 mm^2. The total number of generated meshes was approximately 200,000. 20,000 meshes were particularly assigned to the target street canyon.

Also, second-order upwind was employed as discretization scheme for momentum equation to improve mass conservation. Residuals of less than 10^{-6} for energy, continuity, and ethane were applied as convergence criteria. This number was 10^{-4} for rest of the physical quantities. SIMPLE algorithm was also performed as numerical procedure to solve the NS equation.

3.3. Boundary conditions

As shown in Fig. 2, the logarithmic flow with 1.5 m/s velocity at a height of $7H$, a displacement height (d) of $0.7H$, and a roughness length of 3.3 mm (Uehara et al., 2000) was assumed as the inflow boundary condition. To provide a temperature profile, a simple procedure was performed; first, a constant temperature was assigned to the airflow boundary and after running a pre-simulation, the obtained profile at the outflow was again assumed as the new inflow boundary. This procedure was repeated a few times until a small temperature difference (about 0.1 K) was observed in both inflow and outflow boundaries. Turbulent intensity and turbulent viscosity ratio (the ratio between turbulent viscosity and molecular dynamic viscosity) were also set equal to 10% and 10, respectively (Li et al., 2006).