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A numerical study of diurnally varying surface temperature on flow patterns and pollutant dispersion in street canyons

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HIGHLIGHTS

- Uneven street temperature condition is used to model surface heating effects.
- Significant differences are observed compared with conventional uniform assumption.
- Air pollution inside street canyons is closely linked with thermal stratification.

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ABSTRACT

The impacts of the diurnal variation of surface temperature on street canyon flow pattern and pollutant dispersion are investigated based on a two-dimensional street canyon model under different thermal stratifications. Uneven distributed street temperature conditions and a user-defined wall function representing the heat transfer between the air and the street canyon are integrated into the current numerical model. The prediction accuracy of this model is successfully validated against a published wind tunnel experiment. Then, a series of numerical simulations representing four time scenarios (Morning, Afternoon, Noon and Night) are performed at different Bulk Richardson number (*Rb*). The results demonstrate that uneven distributed street temperature conditions significantly alters street canyon flow structure and pollutant dispersion characteristics compared with conventional uniform street temperature assumption, especially for the morning event. Moreover, air flow patterns and pollutant dispersion are greatly influenced by diurnal variation of surface temperature under unstable stratification conditions. Furthermore, the residual pollutant in near-ground-zone decreases as *Rb* increases in noon, afternoon and night events under all studied stability conditions.

1. Introduction

As a basic element of complex urban built environment, street canyon flow plays an important role in urban ventilation, human comfort and pollutant dispersion. Its flow regimes are mainly determined by canyon geometry, ambient wind condition, atmospheric instabilities, and building layout (Vardoulakis et al., 2003; Georgakis and Santamouris, 2004). Many field measurements, laboratory experiments and numerical simulations have been conducted based on different meteorological and geometrical factors (Li et al., 2006; Allegrini et al., 2014).

Richards et al. (2006) conducted a stratified wind tunnel experiment to analyze the thermal effects of leeward wall heating; he concluded that cavity eddies tend to be strong with ground heating. Offerle et al. (2007) performed a wind and temperature field measurement for a deep urban street canyon in central Gothenburg, Sweden. Materials and locations of walls were found to be closely correlated with the heat exchange and even the flow structure inside street canyons. Niachou et al. (2008a,b) conducted a five-day filed measurement based on an Athens' street canyon where air flow and temperature variations were hourly recorded. They found the vertical stratification of air temperature inside the canyon significantly affected the vortex formation. Allegrini et al. (2013) conducted a wind tunnel measurement to study the influence of buoyancy on the flow changes in a scaled urban street canyon with heated surfaces using particle image velocimetry

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technique. They found solar radiation induced buoyancy plays an important role in street canyon flow field, especially for cases with low free stream velocities.

Meanwhile, street canyon flows have also been intensively studied by using computational fluid dynamics (CFD) approach due to its flexibility and high efficiency prediction of the complex wind flow in building environment (Xie et al., 2005a, 2006; Memon et al., 2010). An early preliminary study conducted by Sini et al. (1995) investigated the flow regimes and pollutant dispersion inside a street canyon using single-surface heating and constant inflow velocity. They revealed the thermal effect plays a remarkable role on air motions. Kim and Baik (1999, 2001) conducted 2D simulations through varying street canyon aspect ratio and bottom surface heating conditions, and identified five flow regimes. Xie et al. (2005b, 2006) performed single-surface heating simulations for street canyons with different canyon geometry configurations. Their results demonstrated the buoyancy force significantly affects air flow structure and air exchange rate of a street canyon. More recently, researches focusing on street canyon ventilation and pollutant transport due to the solar radiation have been performed as well. Qu et al. (2012) adopted a coupled dynamic-radiative CFD model to predict the building thermal effect on local atmospheric environment under relatively low wind speed condition. The thermal stratification was revealed to have a remarkable influence on the local wind flow field formation. Cai (2012) conducted a large-eddy simulation (LES) study of passive scalar transfer and dispersion under single-surface heating conditions for street canyon flows. This study suggests the total resistance to street canyon ventilation becomes more dominated by the near-facet resistance due to the wall heating. Kwak and Baik (2014) conducted more sophisticated 2D Reynolds-Averaged Navier-Stokes (RANS) simulations to investigate NO_x and O_3 exchange between a street canyon and the overlying ambient air, in which solar radiation and chemical reaction between gases were considered.

Although a fairly large body of literature exists in this research field, the investigation based on uneven distribution of the canyon façade (due to variable solar radiation angles during day times) is still limited. Majority of the existing literature are based on single-surface heating assumption with even temperature distribution per canyon facet (Liu et al., 2003; Li et al., 2010). To reveal the diurnal variation of surface heating effects on street canyon flows, simulations using uneven distributed street temperature layouts and multiple-surface heating conditions are performed in this study, to provide detailed examination of street canyon ventilation and pollutant removal performance over unstable stratification conditions.

2. Methods and validation

2.1. CFD model

The CFD model of this study is based on the RANS equations governing fluid flow and transport principles for incompressible turbulent flow in terms of mass, momentum and energy conservation equations. Equations for turbulent kinetic energy and turbulent dissipations rate are solved with RNG k-ε closure scheme. Boussinesq approximation is employed to address temperature induced density variation of air (Kim and Baik, 2001; Kang et al., 2008; Memon et al., 2010). All governing equations are solved by using the commercial CFD code ANASYS Fluent (ANSYS, NH, USA). For more details on the basic model parameters used in this study, refer to Cheng et al. (2009).

To validate the numerical accuracy and obtain a better understanding of fundamental wind-buoyancy-driven flow, the computational domain used in this study is kept identical with the experimental model proposed by Uehara et al. (2000), which consists of 9 uniform street canyons with the ambient air flow direction from the left to the right (Fig. 1). The height H and the width D of the street canyon are both set as 100 mm (aspect ratio of 1). The height of the computational domain is kept at $4H$. The fifth canyon is selected as the target street canyon for results analysis and discussion. Inflow velocity is given by a Power-law profile as:

$$U_z = U_0\left(\frac{Z - Z_H}{Z_{4H} - Z_H}\right)^{\alpha} \tag{1}$$

where U_0 is the reference velocity at $Z = 4H$, and α is the wind profile exponent set as 0.28. Zero gradient boundary conditions are applied at the top and the outlet of the domain; no-slip boundaries are used at all canyon facades.

Grid independency analysis is conducted over five mesh scales to ensure the results are independent of grid configuration (Fig. 2). It is found that the horizontal velocity at the reference point (marked by star) turns to be almost unchanged after mesh refinement above 20 × 20 (corresponding grid interval is 5 mm). Considering the computational efficiency and accuracy, the final grid interval was set as 5 mm in this study.

To evaluate the ventilation and pollutant removal performance under different thermal conditions, a point source of pollutant with the mass flow rate of 0.1 μg/s is placed at the center of the canyon ground to represent an averaged vehicular exhaust rate (Assimakopoulos et al., 2003; Salizzoni et al., 2009).

In addition, half of the street is set as shaded part with a lower temperature and the other half is set as sunlit part with a relatively higher temperature to represent the building shading effect that occurs during morning and afternoon. According to the study conducted by Kwak et al. (2011), reasonable temperature boundary conditions representing four typical time events (morning, noon, afternoon, and night) are predefined to represent a reasonable temperature diurnal variation (Table 1). All building roofs are assumed to be adiabatic and the thermal stratification of the inflow is set as neutral.

Lastly, a user-defined wall function which accounts for heat transfer occurring between the air and the canyon facets (Ciofalo and Collins, 1989; Sini et al., 1995; Kim and Baik, 1999) is introduced in to the current CFD model using a user-defined subroutine, and it is detailed by Eqs. (2)–(4).

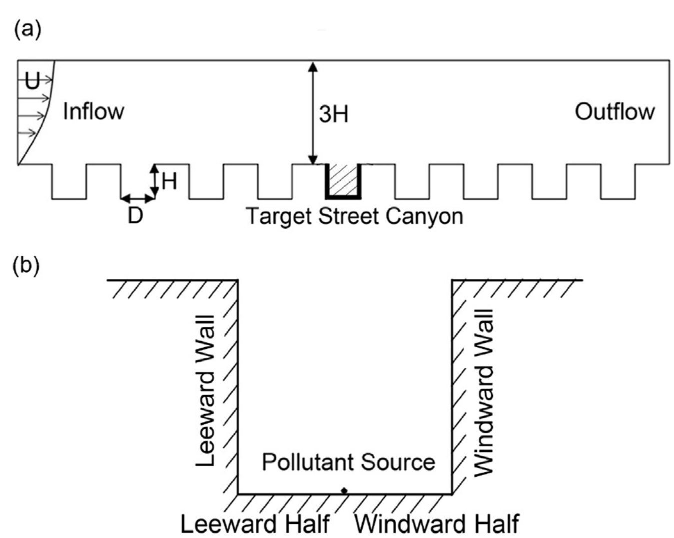

Fig. 1. Schematic diagram of (a) the computational domain with boundary conditions and (b) enlarged view of the target street canyon.