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Numerical simulation of diurnally varying thermal environment in a street canyon under haze-fog conditions

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HIGHLIGHTS

- Light extinction effect of haze-fog is considered in street canyon environment.
- Surface temperature of all facets increases when haze-fog becomes thicker.
- Surface temperature distribution is more even under thicker haze-fog conditions.
- Flow patterns are altered by different haze-fog conditions.
- Thicker haze-fog conditions may lead to more uncomfortable thermal environment.

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ABSTRACT

The impact of haze-fog on surface temperature, flow pattern, pollutant dispersion and pedestrian thermal comfort are investigated using computational fluid dynamics (CFD) approach based on a three-dimensional street canyon model under different haze-fog conditions. In this study, light extinction coefficient (K_{ex}) is adopted to represent haze-fog pollution level. Numerical simulations are performed for different K_{ex} values at four representative time events (1000 LST, 1300 LST, 1600 LST and 2000 LST). The numerical results suggest that the surface temperature is strongly affected by the haze-fog condition. Surface heating induced by the solar radiation is enhanced by haze-fog, as higher surface temperature is observed under thicker haze-fog condition. Moreover, the temperature difference between sunlit and shadow surfaces is reduced, while that for the two shadow surfaces is slightly increased. Therefore, the surface temperature among street canyon facets becomes more evenly distributed under heavy haze-fog conditions. In addition, flow patterns are considerably altered by different haze-fog conditions, especially for the afternoon (1600 LST) case, in which thermal-driven flow has opposite direction as that of the wind-driven flow direction. Consequently, pollutants such as vehicular emissions will accumulate at pedestrian level, and pedestrian thermal comfort may lower under thicker haze-fog condition.

1. Introduction

The increasing trend towards urbanization results in higher anthropogenic emissions which cause more serve urban environment problem all around the world (Holmes et al., 2009; Aruna et al., 2014). Recently, high occurrence of haze-fog events in northern (Zhang et al., 2014; Gao et al., 2015), central and south-eastern (Kang et al., 2013; Gao et al., 2015) China have been recorded and great hazards on public health and urban climate have been reported (Tao et al., 2014). As the main components of haze-fog (Tao et al., 2014), water and dust droplets have significant impacts on atmospheric radiative budget by absorbing and scattering shortwave and longwave radiation (Gómez-Amo et al., 2014; Valenzuela et al., 2015). This can further affect the received solar radiation at urban surface (Elias et al., 2009). Consequently, the canyon surface temperature, canyon flow structure, pollutant dispersion and pedestrian comfort in urban areas are significantly affected (Moonen et al., 2012).

Huang et al. (2005) conducted a field measurement in Tokyo and they found the temperature difference between sunlit and shadow walls in summer is 3–12 °C. Yang and Li (2009) adopted infrared

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thermograph to investigate the diurnal thermal behavior of urban surfaces in Hong Kong during warm and cold periods. They revealed that the surface temperature varies with incident solar radiation and the albedo of urban surfaces, which is confirmed by Kantzioura et al. (2012) and Ahmed et al. (2014). Surface thermal force plays an important role in determining local flow patterns in urban areas (Kim and Baik, 2001). Smith et al. (2001) investigated the flow field and tracer dispersion around an idealized cubical building. They found the building shading effect significantly alters the canyon flow circulation. Based on simplified urban models, Yang and Li (2011) numerically demonstrated the airflow in the street canyon is dominated by thermal stratification when ambient wind is relative small. Allegrini et al. (2014) compared 2D steady CFD simulation results with wind tunnel measurements based on a single street canyon model, and general flow fields and vortex structures for buoyant flows can be successfully predicted with CFD.

Pollutant dispersion analysis is largely relied on the prediction of urban canyon flow patterns. Tsai and Chen (2004) assessed the effect of traffic emissions on the air quality in an urban street canyon using the RNG k-ε model and measurements. They found the traffic flow rate significantly affects the pollutant concentration, and pollutants are more likely to accumulate on the leeward side than the windward side. Numerical results of Xie et al. (2005) indicate that the surface heating induced by solar radiation can lead to a strong buoyancy force, which may increase pollutant concentration in the street canyon. Cheng et al. (2009), Cheng and Liu (2011) examined flow and pollutant dispersion characteristics under different thermal stratifications. They revealed the unstable stratification can promote street canyon ventilation with an improved pollutant removal performance. Cai (2012) studied the transfer and dispersion of a scalar released from one urban facet (i.e. the street, the windward wall, the leeward wall) using large-eddy simulation (LES) approach. The LES results demonstrate distinctive dispersion characteristics for two conditions: the assisting condition in which the thermal-driven flow has the same direction as that of the wind-driven vortex; the opposing condition in which the thermal-driven flow has the opposite direction as that of the wind-driven vortex.

As the surface heating condition is closely related to incident solar radiation, research efforts have also been spent on cases with diurnally varying solar radiation. Kwak and Baik (2014) numerically examined the diurnal variation of NO_x and O_3exchange in a street canyon, in which the differential wall heating is found to be important for determining pollutants exchange. Our previous work (Tan et al., 2015) also studied the influence of uneven surface heating on pollutants dispersion in a street canyon, and significant differences are observed compared with conventional uniformly heated canyon facets.

As a key heat source of street canyon thermal environment, solar radiation significantly influences the pedestrian thermal comfort by influencing surface temperature distribution (Nagara et al., 1996). Lin et al. (2010) investigated the shading effect on long-term thermal comfort, and multiple shading types and different shading levels are recommended to allow users to choose their preferred thermal comfort condition. Makaremi et al. (2012) conducted a field study to investigate the shading effect of buildings and trees on pedestrian thermal comfort in a context of hot and humid climate. They found high shading level in outdoor environments extends the continuity of the acceptable thermal condition. Stavrakakis et al. (2012) proposed a CFD model to assess the microclimate in urban environment, in which the plant evaporation, solar radiation and wind effects are taken into account. Their numerical results can effectively reveal the problematic areas in terms of thermal discomfort and wind effects.

Although numerous studies have been conducted to detail the urban street canyon thermal environment, pollutant dispersion, and even pedestrian comfort due to the variation of incoming solar radiation and ambient flow, studies considering the optical effects (i.e. scattering, absorbing) of haze-fog on incoming solar radiation in street canyons remain very limited. As haze-fog events have been recorded in many metropolis, especially in mid-east areas of China (Li and Liu, 2014), it is very necessary to evaluate and analyze the urban canyon thermal/wind environment during haze-fog episodes. This study presents a computational methodology to reveal impacts of haze-fog on street canyon surface heating, flow patterns, pollutant dispersion and pedestrian comfort during a day. This research can contribute to a more sophisticated numerical modeling approach to better understand the street canyon thermal environment and pollutants dispersion characteristics.

2. Methods

2.1. CFD model

A representative three-dimensional hypothetical street canyon is created (Fig. 1). Buildings and the street canyon are aligned in the x-direction (north-south). Both the building height (H) and street canyon width (W) are set as 20 m, with an aspect ratio of 1. The fluid domain size is 100 m (x-direction) × 60 m (y-direction) × 80 m (z-direction).

No slip boundary condition is applied at all street canyon facets, while the two side planes of the street canyon are set as symmetry. The prevailing ambient wind is introduced along the y direction perpendicular to the street axis. The inflow profile is given by a logarithmic profile (Richards and Hoxey, 1993; Allegrini et al., 2012):

$$U(z) = \frac{u^*_{ABL}}{\kappa} \ln\left(\frac{z+z_0}{z_0}\right) \tag{1}$$

$$k = \frac{u^*_{ABL}2}{\sqrt{C_\mu}} \tag{2}$$

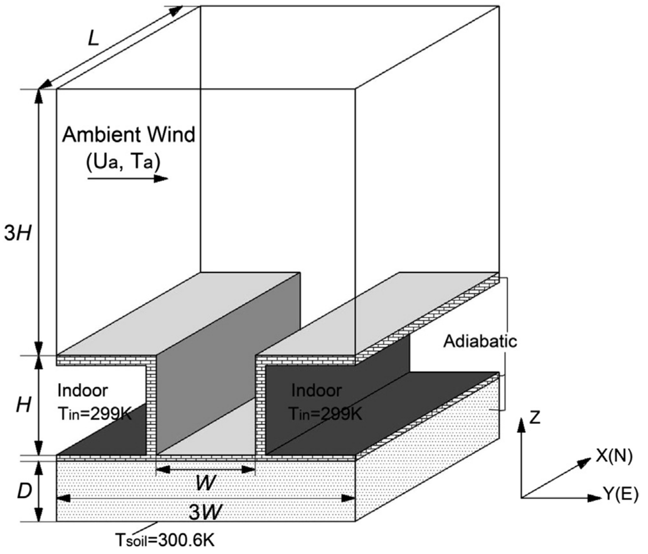

Fig. 1. Schematic diagram of the computational domain (H: 20 m; W: 20 m; D: 2 m; L: 100 m; U_a: ambient wind velocity; T_a: ambient air temperature).