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Numerical Analysis of Building Shadow Effect on Buoyant Flow in Urban Street Canyons

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Abstract

Building shadow effect on buoyant flow patterns due to the variation of diurnal solar radiation, is examined by a two-dimensional street canyon model with the uneven distributed street temperature and a user-defined wall function representing the heat transfer between the air and the street canyon. The prediction accuracy of the developed street canyon model was validated against a published wind tunnel measurement. A series of numerical simulations in four scenarios (Morning, Afternoon, Noon and Night) were performed. Numerical results in terms of velocity and pollutant concentration were examined and correlated with the rotating vortex shapes and sizes in the street canyon. It is demonstrated that the uneven distributed street temperature enhances the buoyancy effect may even change the flow patterns in the street canyons. Conclusively, uneven distributed street ground temperature also plays important roles on pollutant dispersion inside the street canyons, and it cannot be neglected for accurate pollutant dispersion prediction.

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 [1-4]. Under isothermal conditions, flow regimes were categorized into isolated roughness flow, wake interference flow, and skimming flow due to different aspect ratios [5-7]. Street canyon surfaces always exhibits higher temperatures than ambient air by absorbing long-wave and solar radiation. Therefore, surface heating effects on flow patterns need to be examined, and several laboratory experiments, field measurements and numerical simulations were performed to address the thermal effects on street canyon flow patterns. Richards et al.[8] conducted a stratified wind tunnel experiment, the thermal effects of leeward wall heating was analysed. The results demonstrated that cavity eddies tend to be strong with bottom heating. Allegrini et al. [9] measured building facades and ground surfaces heating during day-times, found that the positions of the centres of vortices are changed in different boundary temperatures . Several field experiments [3,10,11] were conducted in different meteorological and geometrical factors, and the vertical stratification of air temperature inside the canyon was proved to have a significant influence on the vortex formation. Meanwhile, computational fluid dynamics (CFD) simulations are conducted to predict the wind flow in urban areas due to the complexity and scale of the built environment[12-15]. Sini et al.[16] use a 2D model to analyse the influence of canyon geometry and surface heating to flow field and pollutant dispersion in urban street canyon, their work demonstrate that CFD is an accurate and effective method to study flow pattern and pollutant dispersion in street canyon. Kim et al. [17,18] indentified five flow regimes through varying street canyon aspect ratio between the building height H and the street width D, and temperature difference between the street canyon bottom and ambient air.

In summary, uniform street temperature is assumed in most of the previous studies, while ignoring its unevenly distributed nature in real situation due to variable solar radiation angles. This assumption may result in inaccurate prediction of the buoyant flow. Therefore, this study aims to investigate the building shadow effect on street canyon flow through introducing uneven street temperature distribution in four thermal conditions, namely morning, noon, afternoon and night. The flow regimes were examined based on predicted streamlines and velocity results, and the induced pollutant dispersion results were assessed as well.

Numerical Model

The numerical model of this study is based on fluid flow and transport principles for incompressible turbulence flow in terms of mass (equation (1)), momentum (equation (2)) and energy (equation (3)) conservation equations. Consequently, equations for turbulent kinetic energy and turbulent dissipations rate are also solved (equation (4), (5)).

$$\frac{\partial \bar{U}_i}{\partial x_i} = 0 \qquad (1)$$

$$\bar{U}_j \frac{\partial \bar{U}_i}{\partial x_j} = (\frac{\rho - \rho_n}{\rho_n}) \mathrm{g}_i - \frac{1}{\rho}\frac{\partial \bar{P}}{\partial x_i} + \frac{\partial}{\partial x_j}(\upsilon \frac{\partial \bar{U}_i}{\partial x_j} - u_i u_j) \qquad (2)$$

$$\overline{U_i} \frac{\partial \bar{\theta}}{\partial x_i} + \frac{\partial\left(\overline{U_i \theta'}\right)}{\partial x_i} = 0 \qquad (3)$$

$$\frac{\partial k}{\partial t} + \frac{\partial}{\partial x_j}\left[\bar{U}_j k - \frac{\upsilon_t}{\delta_k}\frac{\partial k}{\partial x_j}\right] = P_k - \varepsilon + G_b \qquad (4)$$

$$\frac{\partial \varepsilon}{\partial t} + \frac{\partial}{\partial x_j}\left[\bar{U}_j \varepsilon - \frac{\upsilon_t}{\delta_\varepsilon}\frac{\partial \varepsilon}{\partial x_j}\right] = \frac{\varepsilon}{k_{\varepsilon 1}}\left[C_{\varepsilon 1}\left(P_k + G_b\right) - C_{\varepsilon 2}\varepsilon\right] \qquad (5)$$

Where,

$$G_b = -\beta g_j \overline{u_j \theta'} \qquad (6)$$

$$\upsilon_t = C_\mu \frac{k^2}{\varepsilon} \qquad (7)$$

$$P_k = \upsilon_t \times \frac{\partial \overline{U_i}}{\partial x_j}\left(\frac{\partial \overline{U_i}}{\partial x_j}+\frac{\partial \overline{U_j}}{\partial x_i}\right) \tag{8}$$

β is the thermal expansion coefficient in the form

$$\beta = \frac{1}{\rho}\left(\frac{\partial \rho}{\partial \overline{\theta}}\right)_p \tag{9}$$

Table.1 explain basic variables used in the above equations here.

C_μ	δ_k	δ_ε	$C_{\varepsilon 1}$	$C_{\varepsilon 2}$
0.09	1.0	1.22	1.44	1.92

Table 1. Coefficient of $k-\varepsilon$ equation

Boussinesq approximation is employed to address the variation in air density due to air temperature change [12, 17, 19]. The buoyancy force is introduced at the last term on the right side of momentum equation (Equation.2).

According to the wind tunnel experiment, the computational model (Figure 1) used in this study consists 9 identical street canyons with the ambient air flow from the left to the right. The height H and the width D of the street canyons are both set as 100mm with aspect ratio of 1. The height of the domain is kept at 3H, and a 5 mm grid interval is used in both directions. Grid independency analyse were conducted to ensure that the results were not dependent on the particular grid configuration. The fifth canyon is selected as the target street canyon for results discussion.

The inflow velocity profile is given by the power law

$$U_z = U_0\left(\frac{z-z_H}{z_{4H}-z_H}\right)^{\alpha} \tag{10}$$

where U_0 is the reference velocity at Z=4H(400mm) setting as 1.28m/s, the wind profile exponent α is set as 0.28. Zero gradient boundary conditions were applied at the top of the domain and outlet; no-slip solid boundaries were prescribed at street ground and building facades.

In order to take building shadow effects into consideration, half of the street was set as shadow part with a lower temperature and the other half was set as sunny part with a relatively higher temperature in morning and afternoon cases. Detailed temperature boundary conditions for all thermal cases are given in Table 2 based on the study conducted by Kwak et al.[20], and all building roofs are assumed into adiabatic and the thermal stratification of the inflow is set as neutral.

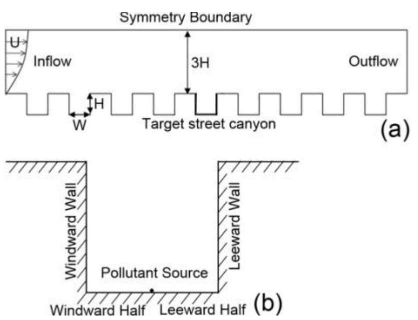

Figure 1. Schematic diagram of (a) the computational domain with boundary conditions and (b) enlarged view of the target street canyon.

Thermal Conditions	**Wind ward Wall**	**Ground**		**Leeward Wall**	**Inflow**
		Wind ward Half	**Leew ard Half**		
Morning	306K	306K	319K	319K	298K
Noon	314K	329K	329K	329K	303K
Afternoon	326K	326K	315K	315K	306K
Night	301K	301K	301K	301K	295K

Table 2.Temperature boundary conditions.

A heat transfer wall function [18, 21] was introduced through a user-defined subroutine to model the heat transfer occurring between the air and the building walls.

$$\frac{Q_w}{\rho C_p} = \frac{U_*^2}{U_f}\frac{(\Theta_f - \Theta_w)}{\Pr_t(1+\phi/s)} \tag{11}$$

$$\phi = 9.24[(\frac{\Pr}{\Pr_t})^{3/4}-1]\times[1+0.28\exp(-0.007\frac{\Pr}{\Pr_t})] \tag{12}$$

$$s = \frac{1}{\kappa}\ln(\frac{z_f}{z_0}) \tag{13}$$

here, U_* is the friction velocity, ϕ the Jayatilleke function, C_p the specific heat at constant pressure, $\Pr$ the Prandtl number, and κ the von Kármán costant with its value of 0.4. The subscripts w and f denote the wall and the nearest grid point from the wall, respectively.

In order to examine pollutant dispersion in the street canyon, a point pollutant source was placed near the street ground at the centre(*x*=950mm, *y*=5mm) releasing inert solid pollutant with the mass flow-rate of 1e-10 kg/s.

Model Validation

Normalized temperature and horizontal velocity along the centreline of the street canyon were compared against with the referred wind tunnel measurements [22]. In order to ensure that the buoyant flow was comparable with the wind tunnel experiment, the *Rb* value of simulated results was kept as -0.21 by setting the reference horizontal velocity of 0.943m/s(U_{2H}). In general, good agreements can be found for horizontal velocity (figure 2) and temperature (figure 3) comparison. However, slight differences are observed within the near wall region for these two variables. This could be due to the simplification of 2D model used in present simulation, while the wind tunnel experiment building blocks are constructed in 3D. The validation results demonstrate that the proposed numerical model is capable to capture characteristics of flow and temperature inside the street canyon in good accuracy.

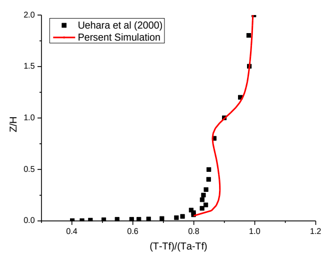

Figure 2. Vertical profiles of normalized potential temperature.

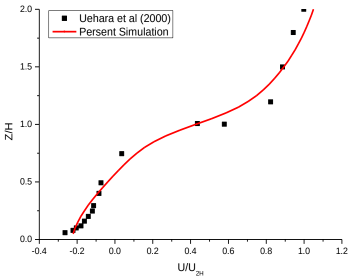

Figure 3. Vertical profiles of normalized horizontal velocity.

Results and Discussion

According to the diurnal variation of solar height, building shadow effects were conducted in the morning and afternoon cases according to prescribed wall temperature distributions setting (table 2). The characteristics of wind flow and pollutant transport in the street canyons were analysed and discussed.

Flow Structure And Pollutant Dispersion

For morning case, comparing with the uniformed assumption (figure 4a), two counter-rotating vortices are observed in the street canyon. Since the air above the leeward half of street is hotter than that above the windward half, the buoyancy force against the predominated clockwise vortex is generated, inducing another counter-clockwise buoyant flow circulation below the main vortex in the right corner of the street canyon. Therefore, the buoyant force induced by uneven street temperature apparently alters the street canyon flow from a single predominated vortex to two counter-rotating vortices. Due to the presence of the lower counter-clockwise-rotating vortex, the pollutant is mainly constrained within its existing region at a lower altitude near the leeward wall.

For the afternoon case, the temperature of windward half of street ground is assumed higher than the leeward half. Similarly, the buoyant force along windward side is also enhanced in this situation. Different from the shrinking trend being evidenced in morning scenario, the main vortex is strengthened and slightly expanded comparing with uniform street temperature assumption (figure 4b). Due to the partially heated windward street surface, the induced buoyancy force further enhances the rotating of the main vortex, Although the flow structure is still similar with that of the uniform street temperature assumption (figure 4b), air velocity in the lower region for the uneven assumption is accelerated to be much more faster. As a result, the pollutant is dispersed from the bottom release region to entire near wall regions of both windward and leeward walls. In contrast, for the uniform temperature assumption, since air velocity is relatively slow, the released pollutant could not be carried to higher altitude, and majority of them are highly concentrated in left bottom corner of the canyon.

Street temperature was set to be uniform both in noon and night based on real situation, and a single predominated vortex appears in both cases. However, significant differences in vortex shapes and sizes are found between them, which is mainly attributed to the distinct buoyancy forces induced by surfaces heating. In noon case, as the ground and windward wall experience higher temperature than the leeward wall, the buoyancy force along the leeward side induced by heated ground confronts with the mechanical clockwise-rotating and damps the downward air velocity near the ground. Consequently, the released pollutant is accumulated at the lower right corner region of the street. In night case, all surfaces experience identical temperature, and the influences of buoyancy are almost vanished. Therefore, the street canyon is dominated by a primary vortex mainly driven by ambient wind flow. The predicted pollutant dispersion is constrained within its windward corner just above the ground.

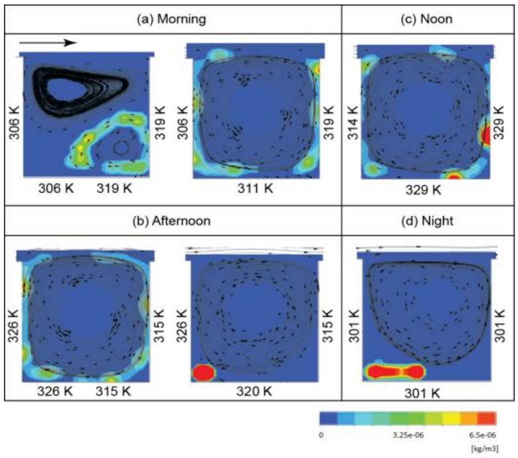

Figure 4. Predicted streamlines and pollutant dispersion results. (a)Morning cases with uneven and uniform street temperature, (b) afternoon cases with uneven and uniform street temperature, (c) noon case and (d) night case.

Velocity Along The Centreline

In order to quantify the extent of the vortex in the street canyon, normalized horizontal velocity along the centreline of the street canyon in the morning and afternoon cases are depicted in figure 5. It is found that the horizontal air velocity in the lower half of the street canyon varies dramatically under different temperature distributions. In detail, comparing with the uniform temperature modelling approach, a significant reverse velocity reduction around 140% is observed within the bottom region ($Z/H < 0.5$) for the morning case with uneven bottom temperature condition. In contrast, the horizontal velocity near the bottom is accelerated by 55% due to the superimpose effect induced by the buoyancy force using the unevenly distributed ground temperature modelling.

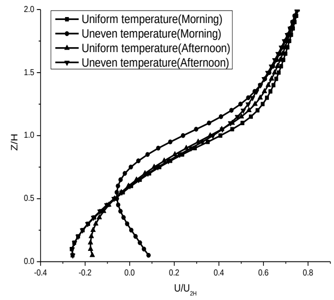

Figure 5. Comparison of normalized horizontal velocity along the centreline of the street canyon in morning and afternoon.

Conclusions

Street canyons flow is induced by both buoyancy and mechanical forces, and these two forces will modify the flow structure and pollutant dispersion characteristics in the street canyons. Through performing a 2D numerical modelling of a typical street canyon in four scenarios (morning, afternoon, noon and night), the influence of building shadow on the ground was investigated. It was found that air flow regimes were greatly influenced by the uniformity of street ground temperature. Comparing with uniform ground temperature assumption, uneven distributed street ground temperature enhances the ground buoyancy effect and partially alters the air circulating patterns inside the street canyon. In addition, uneven distributed street ground temperature also plays important roles on pollutant dispersion inside the street canyons, and it cannot be neglected for accurate pollutant dispersion prediction. This study demonstrates that the unevenly distributed street ground temperature can improve the simulation accuracy of the air flow and pollutant dispersion, and it should be considered in future simulation.

Acknowledgments

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