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Author(s)	**Li, XX; Koh, TY; Britter, R; Liu, CH; Norford, LK; Entekhabi, D; Leung, DYC**
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LARGE-EDDY SIMULATION OF FLOW FIELD AND POLLUTANT DISPERSION IN URBAN STREET CANYONS UNDER UNSTABLE STRATIFICATIONS

Xian-Xiang Li[1,*], Tieh-Yong Koh[1,2], Rex Britter[3], Chun-Ho Liu[4], Leslie K. Norford[1,5], Dara Entekhabi[1,6] , Dennis Y. C. Leung[4]

[1]CENSAM, Singapore-MIT Alliance for Research and Technology, Singapore 117543
[2]School of Physical and Mathematical Sciences, Nanyang Technological University, Singapore 637371
[3]Department of Urban Studies and Planning, Massachusetts Institute of Technology, Cambridge, MA, USA
[4]Department of Mechanical Engineering, The University of Hong Kong, Hong Kong, China
[5]Department of Architecture, Massachusetts Institute of Technology, Cambridge, MA, USA
[6]Department of Civil and Environmental Engineering, Massachusetts Institute of Technology, Cambridge, MA, USA

ABSTRACT

Thermal stratification plays an important role in the air flow and pollutant dispersion processes. This study employed a large-eddy simulation (LES) code based on a one-equation subgrid-scale (SGS) model to investigate the flow field and pollutant dispersion characteristics inside urban street canyons. The unstable thermal stratification was simulated by heating the ground level of the street canyons. The thermal buoyancy forces were, using the Boussinesq assumption, taken into account in both the Navier-Stokes equations and the transport equation for SGS turbulent kinetic energy (TKE).

The LES had been validated against experimental data obtained in wind tunnel studies before it was applied to study the detailed turbulence and pollutant dispersion characteristics in urban street canyons. The effects of different bulk Richardson number (R_b) were investigated. Several typical temperature differences between the street bottom and ambient air were configured to simulate the scenarios occurring at different times during the day.

Key words: Large-eddy simulation (LES); thermal effect; street canyon; pollutant dispersion

1. INTRODUCTION

Numerous studies have been conducted over the past decades to help understand the flow pattern and pollutant transport inside urban street canyons. Thermal stratification (due to solar radiation, anthropogenic heat, etc) plays an important role in the air flow and pollutant dispersion processes. Air circulation and temperature distribution within urban street canyons are of high significance for pedestrian comfort and pollutant dispersion. Usually the traffic exhaust is hotter than ambient air and this fact will also influence the pollutant transport in urban areas. During the field measurement carried out by Niachou et. al. (2008), unstable weather conditions were measured in 85% of the cases in day period, while during night this value still was 64%. Therefore it is very important to study the effect of unstable weather conditions on the urban environment.

With the development of computer hardware and algorithm, the Computational Fluid Dynamics (CFD) technique has become a popular and powerful tool in urban street canyon research due to its efficiency and low cost (Li et. al., 2006). Here we will utilize a sophisticated CFD model to investigate the thermal effect on the urban wind flow and pollutant dispersion.

2. METHODOLOGY

A large-eddy simulation (LES) code for incompressible turbulent flow based on a one-equation subgrid-scale (SGS) model was employed in this study. The thermal buoyancy forces were, using the Boussinesq assumption, taken into account in both the Navier-Stokes equations and the transport equation for SGS turbulent kinetic energy (TKE). The detailed mathematical formulation was discussed in Li et. al. (2008). Following Uehara et. al. (2000), a bulk Richardson number R_b was introduced to quantify the thermal effect over the inertial effect, which was defined as

$$R_b = \frac{gh}{U_h^2} \frac{T_h - T_f}{T_a + 273},$$

(1)

where g is the gravitational acceleration, h is the building height, T_h is the temperature at the roof level, T_f is the temperature at the ground level, T_a is the reference (ambient) temperature, and U_h is the streamwise velocity at the roof level.

Figure 1 depicts the schematic computational domain used in the current study, which represents a typical street canyon in an idealized manner. The spanwise-homogeneous computation domain consists of a street canyon of height h at the bottom and a free shear layer of height h above the building. The background atmospheric flow was simulated in the form of a pressure-driven free stream in the free shear layer only. The air flow boundary conditions are set to be periodic in the streamwise and spanwise directions. No-slip conditions are set at rigid walls. The air temperature at the top is set to be the ambient temperature T_o and the ground level (bottom) maintains a constant temperature $T_a + \Delta T$ (bottom heating). The temperatures at the rigid walls are set to the ambient temperature T_a (case 1) or adiabatic (case 2). In this paper, only case 1 will be studied.

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* Corresponding author:

Dr. Xianxiang Li, CENSAM, Singapore-MIT Alliance for Research and Technology, S16-05-08, 3 Science Drive 2, Singapore 117543. Tel: (65) 6516 2048; Fax: (65) 6778 5654; Email: lixx@smart.mit.edu
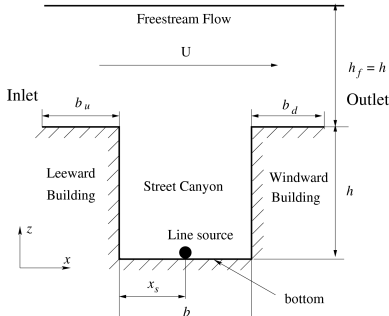
Figure 1: Schematic of computational domain for the flow and pollutant transport in a street canyon with bottom heating.
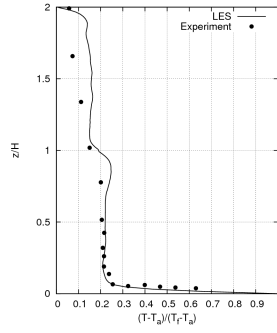

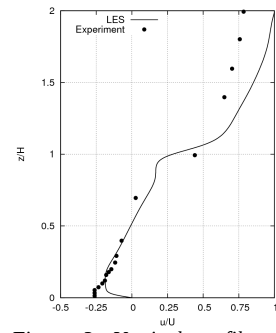Figure 2: Vertical profiles of normalized temperature at the vertical centerline of the unity street canyon.

Figure 3: Vertical profiles of normalized streamwise velocity at the vertical centerline of the unity street canyon.

3. RESULTS

3.1. Model validation

To validate the current model, an LES of a unity street canyon ($h/b = 1$) with bottom heating was carried out, for which wind tunnel measurement results (Uehara et. al., 2000) are available. The R_b numbers were -0.21 and -0.3 in the wind tunnel experiment and the LES, respectively. The comparisons of vertical profiles of normalized temperature and streamwise velocity are shown in Fig. 2 and 3, respectively. It is clear that the agreement between the current LES results and the experimental data is good, especially within the street cavity ($z/h < 1$). The apparent discrepancy of streamwise velocity above the street cavity ($z/h > 1$) was caused by the different freestream velocity used for normalization: the current LES study used the velocity at $z = 2h$ while the experimental results used the velocity at $z = 7h$.

3.2. Airflow pattern

The Reynolds number $Re = \dfrac{Uh}{\nu}$ (U is the freestream velocity, and ν is the kinematic viscosity) used in this study varied from 4000 to 7000, which complies with the criteria suggested by Hoydysh et al. (1974) to ensure that the flow pattern in the street canyon is independent of viscous effects (Meroney et al. 1996).
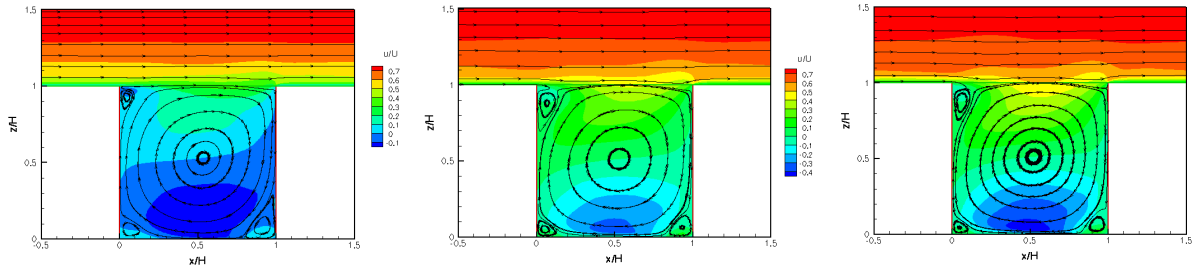

Figure 4: Flow patterns and normalized streamwise velocities under different stratification. R_b: (left) 0; (middle) -3; (right) -5.

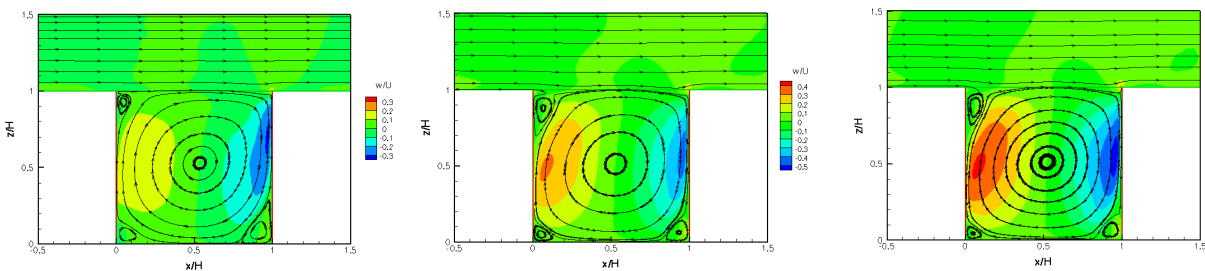

Figure 5: Flow patterns and normalized vertical velocities under different stratification. R_b: (left) 0; (middle) -3; (right) -5.

Shown in Figures 4 and 5 are the flow patterns and normalized velocities in the unity street canyon under different stratification. In the three cases studied, the flow patterns varied little. However, with the increasing unstable stratification, the streamwise velocity at the low half street canyon also increased (Figure 4). With careful examination it was found the wall friction at the ground level increased due to the higher velocity gradient. As a result, at higher R_b number, higher pressure difference should be prescribed at free stream to maintain the same freestream velocity as in lower R_b number case.

The vertical velocities (both downward and upward) were greatly strengthened when Rb number increased. For pollutant removal, this means the leeward updraft will bring more pollutants to the roof level but the windward downdraft will take more pollutants back to the ground level. However, since the turbulence intensities at the roof level were also

strengthened with increasing unstable stratification (not shown here), the pollutant removal from the street canyon was enhanced. The effect of this enhancement will be shown below in the pollutant distribution.

3.3. Temperature distribution

Figure 6 depicts the normalized temperature distribution $(T-T_a)/(T_r-T_a)$ at R_b = -3 and -5. It is seen that the temperature distribution largely followed the flow trajectory. In the core region, the temperature was rather uniform (between 0.125 and 0.1). In the lee side of the street canyon, the temperature was higher than the windward side. With the increasing R_b number, the temperature at a fixed position also increased.
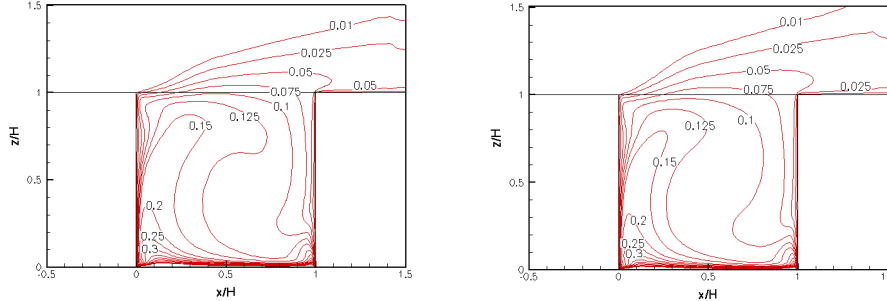

Figure 6: Normalized temperature distribution under different stratification. R_b: (left) -3 and (right) -5.

3.4. Pollutant dispersion

The pollutant release from a line source located at the center of the ground level was simulated as a passive scalar. Its normalized concentration distribution c/C_0 in a unity street canyon under different stratification is contrasted in Figure 7, where C_0 is the concentration of the source. The pollutant was convected by mean flow and diffused by turbulent after released from the source (Li et al., 2009). As the vertical velocities were strengthened with increasing unstable stratification (figure 5), the convection of pollutants were enhanced. Therefore, the pollutant concentration inside the street canyon decreased with increasing R_b number. On the other hand, the pollutant concentration outside the street canyon increased with increasing R_b number. It is evident that the buoyancy force helps better disperse the pollutant.
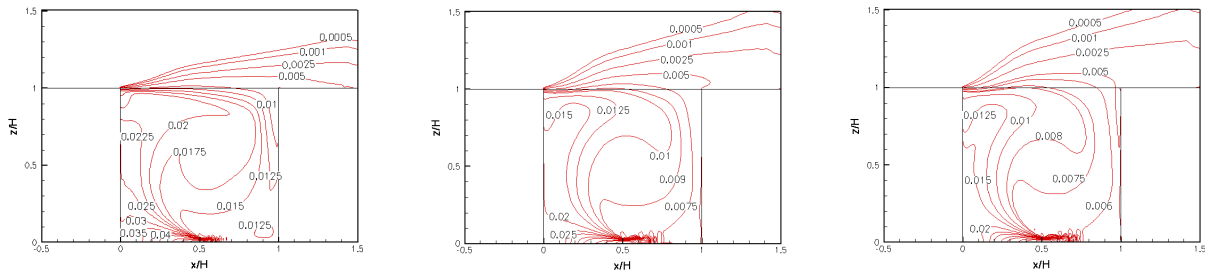

Figure 7: Normalized pollutant concentration distribution under different stratification. R_b: (left) 0; (middle) -3; (right) -5.

4. CONCLUSIONS

This paper employed a large-eddy simulation (LES) code to investigate the flow field and pollutant dispersion inside the urban street canyon under different unstable stratification. The buoyancy force was included in the vertical momentum equation and the transport equation for subgrid-scale turbulent kinetic energy with Boussinesq assumption. Three cases with R_b number 0, -3, and -5 were studied to explore the effect of unstable stratification on the urban wind and thermal environment.

Although the cases studied here did not show significant changes in flow pattern, some enhancement in both streamwise and vertical velocities were found.

It was shown that the increasing unstable stratification will facilitate the removal of pollutant from the street canyon. This is a natural consequence of the increase flow updraft resulting from bottom heating.

The future study will focus on the high R_b number cases, in which the flow pattern changes will be more significant. As a result, more profound impact on the pollutant dispersion will also be expected.

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