Large-eddy simulation of turbulent transport in urban street canyons in different thermal stabilities

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ABSTRACT: Three scenarios of large-eddy simulation (LES) were performed to examine the characteristic flow and pollutant dispersion in urban street canyons under neutral, unstable and stable thermal stratifications. Street canyons of unity aspect ratio with ground-heating or -cooling are considered. In the LESs of the thermal stabilities tested, a large primary recirculation is developed in the center core and the turbulence production is dominated at the roof level of the street canyon. The current LES results demonstrate that unstable stratification enhances the mean wind, turbulence and pollutant removal of street canyons. On the other hand, in stable stratification, which has been less investigated in the past, the ground-level mean wind and turbulence are substantially suppressed by the large temperature inversion. Whereas, the weakened recirculating wind in the street canyon results in a larger velocity gradient that increases the turbulence production at the roof level. It also slows down the turbulence being carried from the roof down to the lower street canyon. Therefore, a higher level of turbulent kinetic energy (TKE) is retained at the mid-level of the windward side in the stably stratified street canyon.

1 INTRODUCTION

More than 3 billion people currently reside in urban areas in the world (World Urbanization Prospects 2007). Their lives and health are tightly affected by the urban meteorological conditions, such as temperature, humidity and air quality. The understanding of urban climate is therefore necessary to improve the living quality of urban inhabitants.

Urban climate is largely determined by the city morphology and the natural atmospheric conditions such as wind and thermal stratifications. Owing to the complicated building geometry, the flow and turbulence in urban areas are different from those in rural areas. Therefore, the conventional theories for the atmospheric boundary layer (ABL) over rural areas should be applied cautiously in the urban ABL (UABL). In view of the existing knowledge gap, a lot of field campaigns have been performed to determine the empirical correlations between atmospheric turbulence and city morphology (Roth 2000). However, the extremely heterogeneous building structures in cities sometime result in difficulties interpreting the measurement data in a controllable manner. Hence, results from laboratory experiments or mathematical modeling are required to complement the existing theories, which, however, are rather limited in the literature.

Owing to the deteriorating air quality commonly found in mega cities, the urban climate community also focuses on the removal of air pollutants from street level to the ABL. Extensive studies have been performed to elucidate the mechanism of pollutant removal from idealized street canyons of different building-height-to-street-width (aspect) ratios to the urban canopy layer aloft. Apart from building configurations, there is rising concern on the correlation between pollutant removal and thermal stratifications. However, the studies in that regard are rather limited.

In this study, large-eddy simulations (LES) were performed to examine the turbulence characteristics and the transport of pollutant for two-dimensional (2D) idealized street canyons in neutral, stable and unstable thermal stratifications. There are a few experimental (Uehara et al. 2000) and LES (Li et al. 2009, Cai 2009, Cheng et al. 2010) datasets for unstably stratified street canyons available in literature, both the turbulence and pollutant removal are generally promoted by buoyancy. On the other hand, there is only a handful of experimental results (Uehara et al. 2000, Rafailidis 2001) for stable stratification. As such, this study was conceived to investigate the detailed coupling among the flow, turbulence and pollutant dispersion of urban street canyons in different atmospheric stability conditions.

2 METHODOLOGY

The LESs were carried out by the open-source computational fluid dynamics (CFD) code, OpenFOAM (OpenFOAM 2010). The subgrid-scale (SGS) motions are modeled by the one-equation TKE transport model (Schumann 1975). Three sets of LES, representing the flow and the pollutant transport in street canyons in neutral, stable and unstable stratifications, are conducted.

2.1 *Governing equations*

In an LES, a filter is applied to decompose the variables into their resolved-scale (denoted by overlines) and SGS components. The model consists of the filtered continuity equation

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

and the filtered momentum equation

$$\frac{\partial \overline{u}_i}{\partial t} + \frac{\partial}{\partial x_j}\overline{u}_i\overline{u}_j = -\Delta P \delta_{i1} - \frac{\partial \overline{p}}{\partial x_i} + \left(\nu + \nu_{\mathrm{SGS}}\right)\frac{\partial^2 \overline{u}_i}{\partial x_j \partial x_j} + \alpha g \theta \delta_{i3}. \tag{2}$$

The index notation is used where u_i is the velocity, t the time, x_i the spatial coordinates, ΔP the large-scale pressure difference, p the kinematic pressure, ν the kinematic viscosity, α the thermal expansion coefficient, g the gravitational acceleration, θ the temperature difference and δ the Kronecker delta. The eddy viscosity, ν_{SGS}, is modeled by $C_k k_{\mathrm{SGS}}^{1/2}\Delta$, where C_k (= 0.07) is a modeling constant and Δ the filter width. The SGS turbulent kinetic energy (TKE, k_{SGS}) is calculated solving its transport equation

$$\frac{\partial k_{SGS}}{\partial t} + \frac{\partial}{\partial x_i}\left(k_{SGS}\overline{u}_i\right) = 2\nu_{\mathrm{SGS}} - C_\varepsilon \frac{k_{SGS}^{3/2}}{\Delta} + \left(\nu + \nu_{\mathrm{SGS}}\right)\frac{\partial k_{\mathrm{SGS}}}{\partial x_i \partial x_i} + \frac{\alpha g \nu_{\mathrm{SGS}}}{\mathrm{Pr}}\frac{\partial \theta}{\partial x_i}\delta_{i3} \tag{3}$$

where Pr (= 0.72) is the Prandtl number and C_ε (= 1.05) is an modeling constant.

To model the thermal energy and the pollutant dispersion, the transport equations of θ

$$\frac{\partial \overline{\theta}}{\partial t} + \frac{\partial}{\partial x_i}\overline{\theta}\,\overline{u}_i = \frac{\nu + \nu_{\mathrm{SGS}}}{\mathrm{Pr}}\frac{\partial^2 \overline{\theta}}{\partial x_i \partial x_i} \tag{5}$$

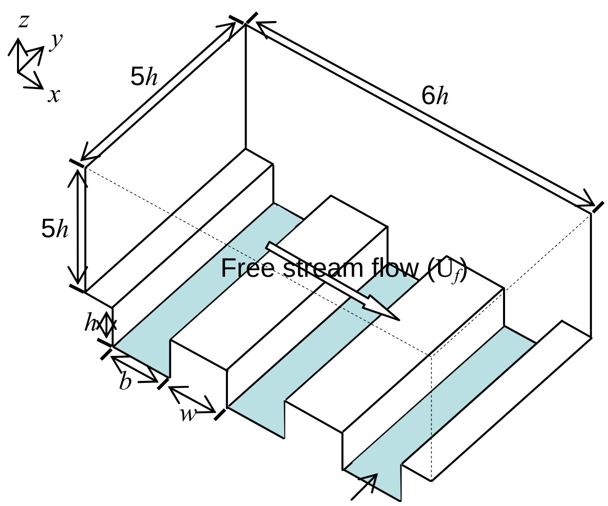
and pollutant concentration c

$$\frac{\partial \overline{c}}{\partial t} + \frac{\partial}{\partial x_i} \overline{c}\, \overline{u}_i = \frac{\nu + \nu_{\mathrm{SGS}}}{\mathrm{Sc}} \frac{\partial^2 \overline{c}}{\partial x_i \partial x_i} \tag{6}$$

are solved where Sc (= 0.72) is the Schmidt number.

2.2 *Computational domain and boundary conditions*

The LES computational domain composes of three identical idealized two-dimensional (2D) street canyons of unity aspect ratio ($h = b = w$; Figure 1). The free-stream flow is set along the x direction perpendicular to the street canyons. Free-slip boundaries, $\overline{\theta} = 0$ and $\partial \overline{c} / \partial z = 0$, are applied at the top of the domain. Cyclic boundary conditions for the flow are employed in the horizontal directions. For the pollutant transport, cyclic boundaries are only used in the y direction. In the x direction, the inflow is assumed to be free of pollutant while the open boundary condition ($\partial \overline{c} / \partial t + \overline{u} \partial \overline{c} / \partial x = 0$) is used at the domain outflow. The building facades and the streets are prescribed as stationary walls on which the zero-gradient boundary conditions of $\overline{\theta}$ and $\overline{c}$ are used. Constant $\overline{\theta}$ (= θ_0) and $\overline{c}$ (= c_0) are applied on the streets to simulate the thermal stratification and pollutant sources, respectively. The Spalding's law of the wall (Spalding 1962) is adopted in the near-wall treatment.



Constant pollutant concentration c_0 and temperature θ_0.

Figure 1. Computational domain.

The Reynolds number Re (= $\mathrm{U}_f h / \nu$) equals 6000-10000 and the bulk Richardson number Rb (= $\alpha g h (\overline{\theta}_h - \overline{\theta}_0) / u_h^2$) equals -0.08 (unstable), 0 (neutral) and 0.3 (stable) in the LESs. Here, u_h and θ_h are, respectively, the values of $\overline{u}$ and $\overline{\theta}$ at the roof center of the street canyons. The spatial resolution is listed in Table 1. The statistics are collected for 25-50 h/U$_f$ at 0.1 h/U$_f$ interval. The results reported in this paper, which are denoted by <·>, are averaged in both the spanwise (homogeneous) direction and the temporal domain.

Table 1. Number of grid points ($N_x \times N_y \times N_z$).

	Canyon ($h \times 5h \times h$)	Shear-layer ($6h \times 5h \times 6h$)
Neutral	50×200×50	300×200×200
Stable/unstable	100×200×100	450×200×100

3 RESULTS AND DISCUSSIONS

3.1 *Mean flow pattern*

Inside the street canyon, a primary recirculation is developed in all the neutral, stable and unstable stratifications (Figure 2). The recirculating structures are almost the same in the neutrally and unstably stratified street canyons that is also found in Li et al. (2009). A small difference, which is the development of the stronger ground-level counter-clockwise-rotating secondary recirculations, is observed in the stably stratified street canyons. Different from the neutral stratification, the mean speed inside the street canyon increases and decreases slightly, respectively, in the unstable and stable stratifications (Figures 2). A notable decrease in the mean speed at the ground-level leeward corner is found in the stable stratification. It is caused by the local cold air accumulation suppressing vertical air movements under strong temperature inversion. Moreover, the primary recirculation leans slightly toward the roof-level windward corner and a stronger secondary recirculation is initiated at the ground-level leeward corner, collectively suggesting that the flow patterns in street canyons are more sensitive to stable than unstable stratifications.

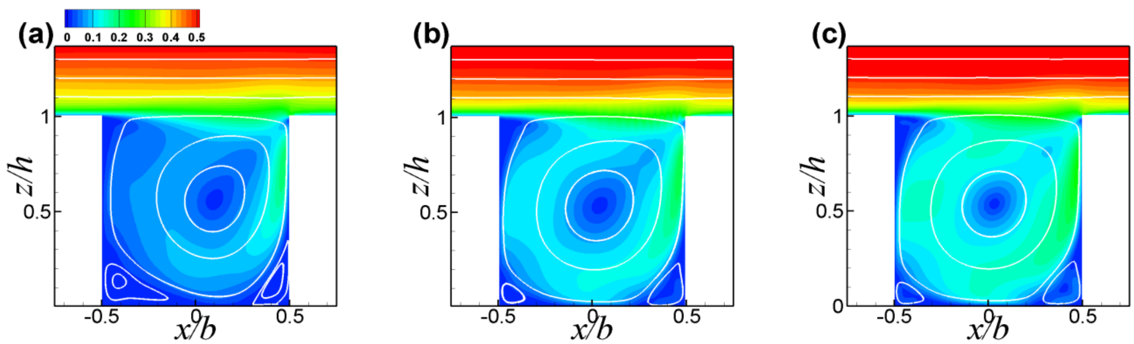


Figure 2. Contour of mean wind speed and streamlines in (a) stable, (b) neutral and (c) unstable conditions.

3.2 *Turbulent characteristics*

The vertical profiles of the standard deviations of the resolved-scale velocity components ($\langle u''u''\rangle^{1/2}$ and $\langle w''w''\rangle^{1/2}$; Figure 3) and the vertical momentum flux ($\langle u''w''\rangle^{1/2}$; Figure 4) are calculated to contrast the contributions of thermal stratifications to the street-level turbulence intensities. The vertical profiles are collected at five different positions of the street canyon in the streamwise direction in which $x/b = 0$ is at the middle (Figure 1). While the LES results agree well with other wind tunnel data in neutral stratification (Cheng and Liu 2010), the velocity standard deviations in different stabilities are smaller than those in the wind tunnel experiment (Uehara et al. 2000). This discrepancy is probably due to the different building geometry in which 3D building cubes and 2D street canyons are used, respectively, in Uehara et al. (2000) and the current LES.

Among the different thermal stratifications considered in this study, the magnitude of the velocity standard deviations is least in the neutral stratification. Apparently, this lower level of turbulence is not caused by the coarser mesh used in the LES in neutral stratification but the different turbulence production mechanisms in unstable and stable stratifications. In the unstable stratification, buoyancy-driven updraft is initiated near the street. The thermal-induced shear subsequently promotes the turbulence intensities compared with that in the neutral stratification. On the other hand, suppressed turbulence is observed near the ground level in the stable stratification. The reduced recirculating speed in the core of the street canyon leads to a larger vertical velocity gradient. The stronger wind shear between the street canyons and the urban canopy layer ends up with elevated turbulence productions. Besides, the turbulence in the vicinity over the roof level is unable to penetrate into the street canyon. The accumulated TKE further promotes the turbulence intensities which even exceed those in the unstable stratification.

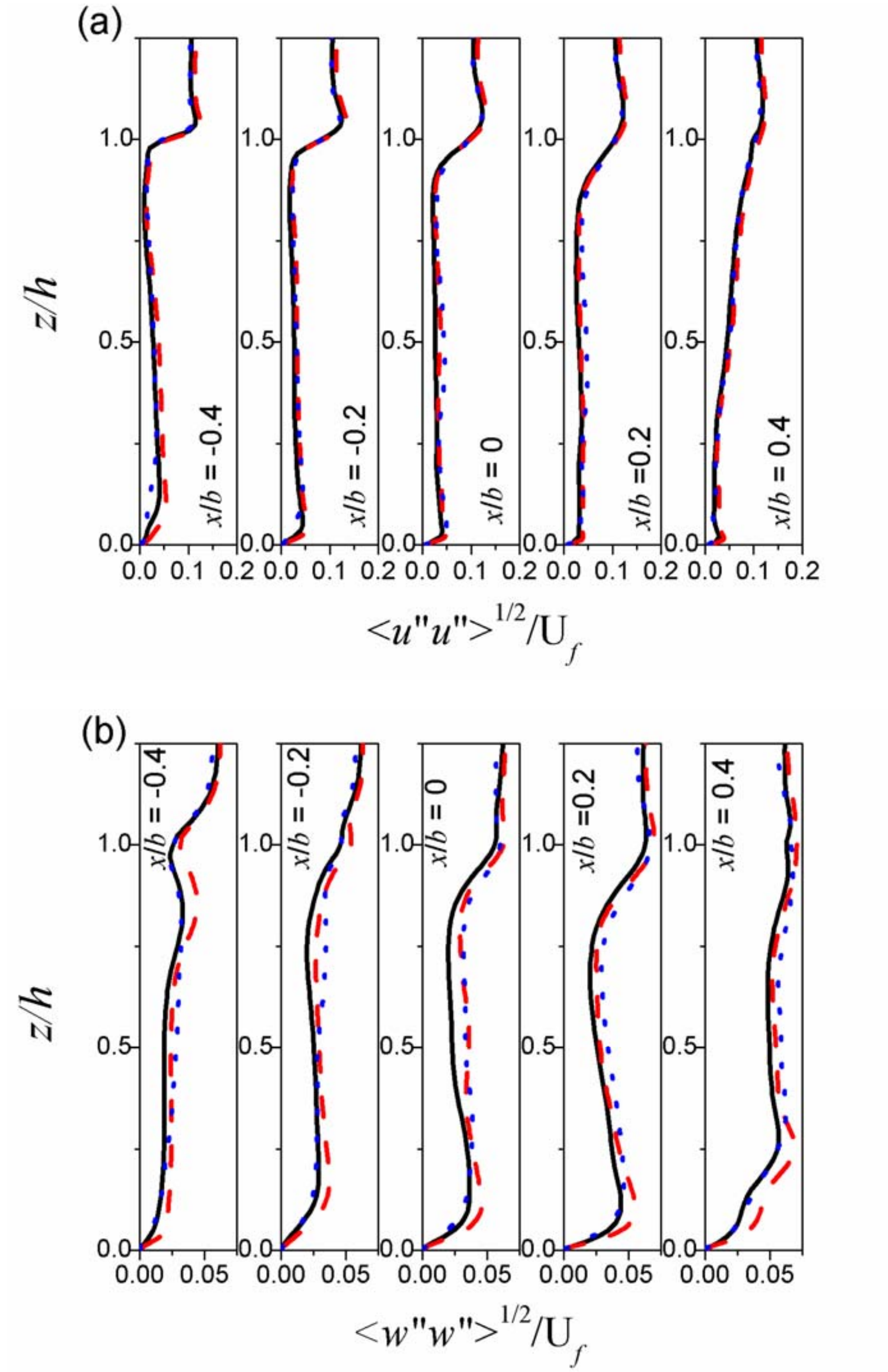


Figure 3. Vertical profiles of the (a) streamwise and (b) vertical velocity standard deviations in different thermal stratifications. Black solid line: Neutral; Red dashed line: unstable; Blue dotted line: stable.

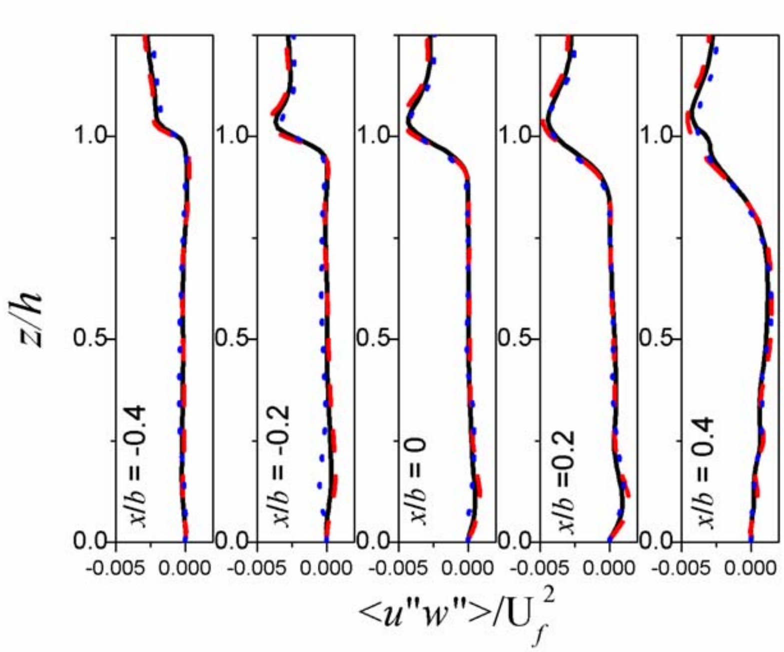


Figure 4. Vertical profiles of the shear stress in different thermal stratifications. Black solid line: Neutral; Red dashed line: unstable; Blue dotted line: stable.

In contrast to the mean speed and the standard deviations of velocity, the vertical momentum, flux <*u″w″*> is less affected by the thermal stratifications (Figure 4). The constant streamwise pressure difference ΔP in different stratifications is the key factor that dominates the background driving force. At the roof level where the prevalent wind flows in the streamwise direction, <*u"w"*> governs the vertical exchange of the streamwise momentum. It is slightly enlarged in the unstable stratification but the change is unnoticeable in the stable stratification. In the mid level of the street canyon, the LES results in different thermal stratifications exhibit similar profiles, suggesting that the momentum transport in the core of the street canyon is less sensitive to the thermal stratification. Comparatively, the difference is more obvious near the ground level ($0 < z/h < 0.2$) where the vertical momentum flux increases slightly in the unstably stratification. On the other hand, a different pattern of vertical momentum flux is observed in the stable stratification. In particular, at $x/b = -0.2$, the vertical momentum flux reverses its direction to negative in $0 < z/h < 0.2$ which is in contrasts to that in the other two stratifications. This change in the direction of momentum transport is likely caused by the ground-level counter-clock-rotating secondary recirculation on the leeward side.

3.3 *Pollutant transport*

The LES-calculated pollutant dispersion behaviors reveal that the pollutant removal is improved in the unstable stratification. Both the mean flow and turbulence are strengthened that collectively promotes the pollutant removal resulting in a lower level of average pollutant concentration in the street canyon (Figure 5). On the other hand, a totally different pollutant dispersion pattern is found in the stable stratification. A shallow layer of elevated pollutant concentration is found near the street level ($z/h < 0.3$), suggesting that the strong temperature inversion retains most of the pollutants at the street level. Local maxima of pollutant concentration variance $\langle c''c'' \rangle^{1/2}$ are observed near the ground level in view of the high local pollutant concentration (Figure 6). Because of the accumulated pollutant, $\langle c''c''\rangle^{1/2}$ in the stable stratification is much higher than its neutral and unstable counterparts.

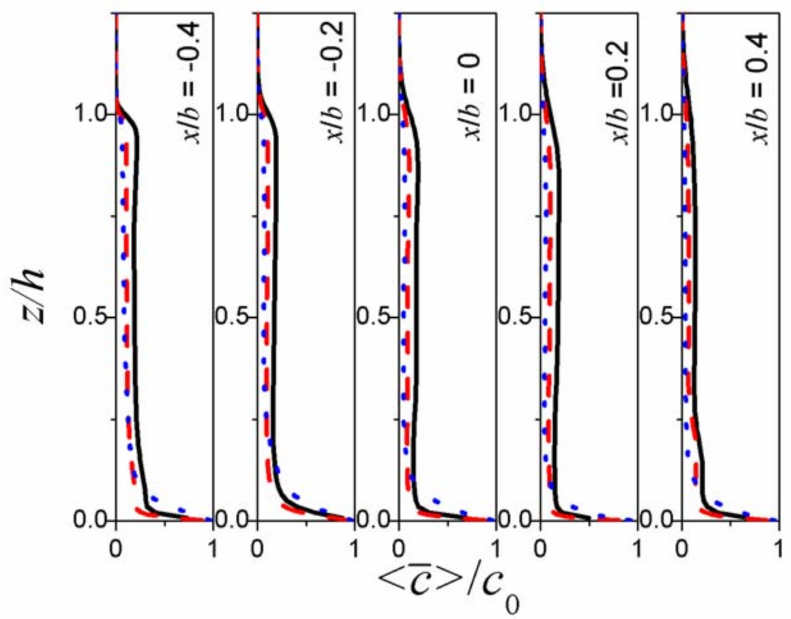


Figure 5. Vertical profiles of averaged pollutant concentration in different thermal stratifications. Black solid line: Neutral; Red dashed line: unstable; Blue dotted line: stable.

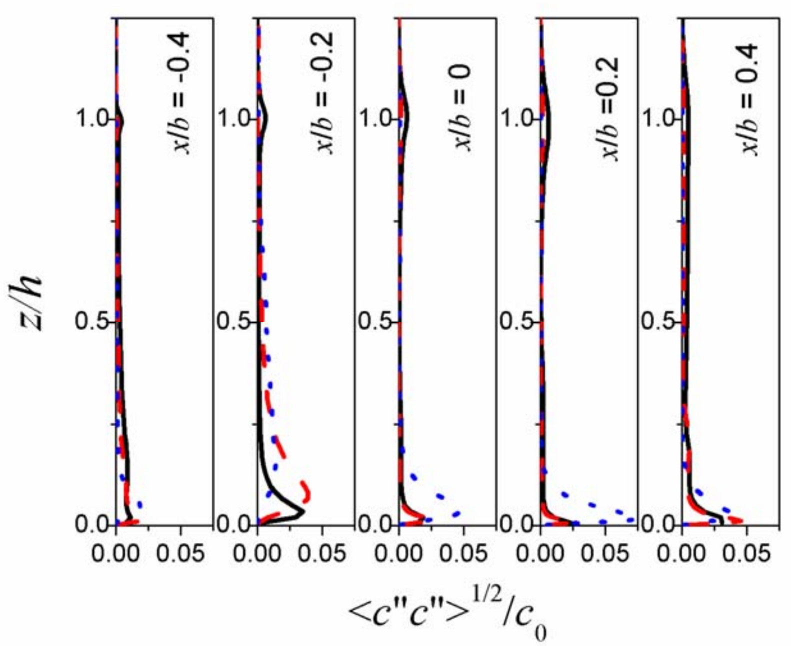


Figure 6. Vertical profiles of averaged pollutant concentration variances in different thermal stratifications. Black solid line: Neutral; Red dashed line: unstable; Blue dotted line: stable.

4 CONCLUSION

Large-eddy simulations (LES) were performed to examine the characteristic flow and pollutant dispersion in street canyons of unity aspect ratio in neutral, unstable and stable stratifications. The results show that the flow structures are more sensitive to the stable stratification compared with those in the neutral and unstable stratifications. In the unstable stratification, enhanced mean flow and turbulence are observed in the street canyons but the flow pattern is similar to the neutral stratification. As a result, an improved pollutant removal performance is observed. In the stable stratification, a shallow layer of strong temperature inversion is found at the ground-level leeward corner that suppresses the street-level pollutant removal. Unexpectedly, an elevated turbulence level is observed in the center core of the street canyon that could be caused by the weakened primary recirculation. The stronger wind shear between the urban canopy layer and the core of the street canyon promotes the turbulence production. In addition, the isolated primary recirculation in temperature inversion implies that most of the TKE is unable to penetrate down to the street level. The combined effects lead to the peak turbulence level in the center core of the street canyon in the stable stratification.

After this preliminary study, another LES of higher resolution for neutral stratification will be performed. Moreover, LESs in a range of thermal stratifications will be undertaken to elucidate the characteristic flow and pollutant removal in urban street canyons.

5 ACKNOWLEDGEMENTS

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