LARGE-EDDY SIMULATION OF WIND FLOWS AND POLLUTANT TRANSPORT INSIDE AND OVER IDEALIZED URBAN STREET CANYONS IN UNSTABLE THERMAL STRATIFICATION

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Abstract: Large-eddy simulation (LES) is employed to study the behaviour of wind flows and pollutant transport both inside and over idealized urban street canyons. The street canyon ventilation performance in different intensities of unstable thermal stratification is compared with an isothermal (reference) case. The one-equation subgrid-scale (SGS) model is adopted to model the SGS transport. Three values of building-height-to-street-width (aspect) ratios, 0.5, 1 and 2, are considered in the study. A constant background pressure gradient is applied in the streamwise direction to drive the prevailing wind above the building array. Periodic boundary condition is assigned to the horizontal domain extent simulating the infinitely long street canyons and the fully developed flows over hypothetical urban areas. The domain top and the bottom urban surfaces are kept at different (constant) temperatures to develop the unstable thermal stratification. The buoyancy force is modelled by Boussinesq approximation whose strength is controlled by the gravitational acceleration constant. Pollutant is released continuously from the ground level of the first street canyon that is removed from the computational domain via the outlet by the open boundary condition.

Above the street canyons, with the enhanced convective motions, the mean wind velocity profile is steeper near the urban surface and is more uniform above, whilst the turbulence intensities (normalized by the mean wind speed) are stronger above the urban surface. In isothermal conditions, the flows exhibit a semi-logarithmic mean velocity profile above the street canyons. In unstable stratification, the mean velocity profile is different from its isothermal counterpart whose deviation depends on the intensity of stratification. To examine the mean velocity profile at different stratifications, the conventional semi-logarithmic equation is modified by adding a linear function $\alpha z/L$ to the logarithmic equation to account for the contributions from buoyancy force. Here α is an empirical constant and L is Monin-Obukov length. The ventilation performance of street canyons is characterized by the air exchange rate (ACH), pollutant exchange rate (PCH), pollutant retention time and average pollutant concentration. The rate of vertical pollutant dispersion is stronger when unstable stratification exists. All these indicators consistently imply that the ventilation performance improves with increasing (unstable) stratification intensity.

Key words: *Large-eddy simulation, urban street canyons, unstable thermal stratification.*

INTRODUCTION

Air pollution problems caused by vehicular exhaust and other anthropogenic pollutant sources inside urban cities have long been a serious concern of residents, urban planners, environmentalists, politicians and researchers of many developed countries. In urban areas, the existence of buildings reduces the wind flows in the streets. The pollutant released at the street level is trapped by the buildings and the subsequent pollutant accumulation would lead to elevated concentrations that may be harmful to the pedestrians and local residents. To gain a deeper understanding to tackle the problems, many researchers have investigated the dependence of ventilation and pollutant dispersion on various factors such as prevailing wind speed and direction, building-height-to-street-width ratio, building geometry, background wind turbulence, traffic-induced turbulence, and buoyancy effect due to thermal stratification, etc. (Li et al., 2006; Ahmad et al., 2005; Vardoulakis et al., 2003).

From the literature, numerous researches have been focused on effects of the different types of idealized urban morphology on the wind flows and pollutant transport inside and over street canyons. Specifically, many researchers studied the problems by varying the building-height-to-street-width ratio (or aspect ratio, h/b, where h is the building height and b is the street width) of urban street canyons separated by rectangular buildings of uniform height in neutral stratification (Cheng and Liu 2011; Li et al., 2008; Liu et al., 2004; Pavageau and Schatzmann, 1999). For instance, Oke (1988) identified three regimes of flow over 2D rectangular buildings, namely, (i) isolated roughness for $h/b < 0.3$ in which the flows around individual building elements do not interact with each other and the prevailing flows are able to reach the ground surface; (ii) wake interference for $0.3 < h/b < 0.65$ in which the wake behind a building element interacts with the next building element and the prevailing flows are not able to reach the ground surface before encountering the next one; and (iii) skimming flow for $h/b > 0.65$ in which flow recirculation(s) is formed between two buildings that is isolated from the prevailing flows aloft.

Unfortunately, due to the additional complexity of the presence of buoyancy, the studies of thermal stratification effect on flows and pollutant transport are relatively less in the literature. Thermal stratification is developed in urban areas when the temperatures on urban surfaces, which could be induced by solar radiation, radiative cooling or anthropogenic heat, are different from that in the prevailing flows. It activates convective motions (depending on the heating configuration such as ground heating, or leeward/windward façade heating) that subsequently modify the flows inside the street canyons and over the entire urban roughness. The relative contribution between prevailing flows and buoyancy to the dynamics is measured by the bulk Richardson number *Ri*. Xie et al. (2007) found that heating on ground and leeward façade strengthens the street-canyon recirculation and improves the ventilation. On the other hand, heating on windward façade increases the resistance of street-canyon recirculation that weakens the ventilation. In view of its complexity compared with that in isothermal conditions, Kim and Baik (2001) proposed five flow regimes based on the aspect ratio and heating intensity. Most of the literature about thermal stratification focused on either the micro-scale environment inside a street canyon or the meso-scale environment above urban roughness, however, the coupling between these two scales and the collective effect on the neighbouring street canyons are overlooked.

In this paper, the study of the wind flows and pollutant transport both inside and above idealized urban street canyons in slightly unstable thermal stratification using large-eddy simulation (LES) will be discussed. In addition, the ventilation performance of street canyons in such conditions will be evaluated using air exchange rate (ACH), pollutant exchange rate (PCH), pollutant mean concentration and pollutant retention time.

METHODOLOGY

LES equipped with the one-equation subgrid-scale (SGS) turbulence model is utilized to study the problem. OpenFOAM, an open-source computational fluid dynamic (CFD) code (www.openfoam.com), of version 2.1.0 is employed for the domain construction, mesh generation and numerical processing.

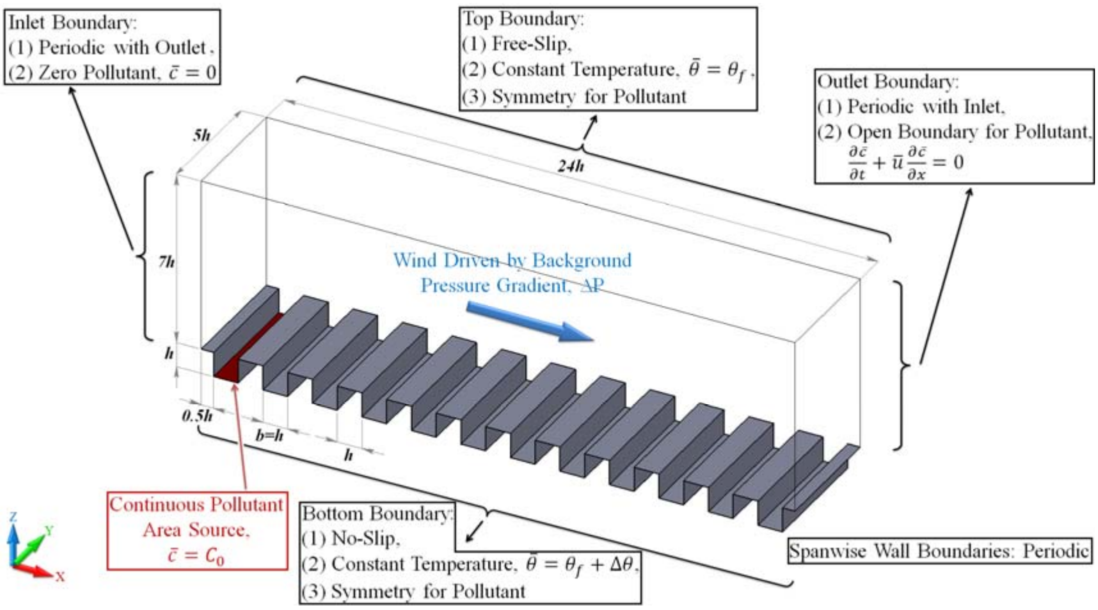

Figure 1. Computational domain and boundary conditions.

The three-dimensional (3D) domain consists of a free-stream layer and a number of street canyons separated by square building elements (Figure 1). The height of the free-stream layer is $H = 7h$. The aspect ratios of street canyons adopted in this study include $h/b = 0.5$, 1 and 2 and the corresponding numbers of street canyons are 8, 12 and 16 such that the domain length remains unchanged. The wind in the free-stream layer is driven by a background pressure gradient ΔP in the direction perpendicular to the street axis. The buoyancy force due to slightly unstable thermal stratification is modelled by Boussinesq approximation such that the density can be considered constant in the governing equations except the buoyancy force term that is added as a momentum source in the form of linear function of temperature. To simulate the two-dimensional (2D) characteristics, the spanwise boundaries are set to periodic for all variables. For the boundary conditions of the flows, the top boundary is free-slip, the urban surface is no-slip and the domain inlet-outlet is periodic. For the temperature, constant values are assigned to the domain top θ_f and the urban surface $\theta_f + \Delta\theta$. The domain inlet-outlet is prescribed as periodic. For the pollutant, a constant area source C_0 is assigned on the ground surface of the first street canyon, the top and the urban surface are symmetric boundaries, zero concentration is assumed at the domain inlet and open boundary condition is assigned to the domain outlet.

In this LES study, the field variables (velocity, pressure, temperature and pollutant concentration) are decomposed into resolved-scale and subgrid-scale (SGS) components using the box filter, in which the filter width is the grid size, $\Delta = (\Delta_x\Delta_y\Delta_z)^{1/3}$. The variables are solved numerically by the continuity, momentum conservation, energy equation and pollutant transport in filtered forms. The filtered momentum conservation equation is as follow

$$\frac{\partial \overline{u}_i}{\partial t} + \overline{u}_j \frac{\partial \overline{u}_i}{\partial x_j} = -\frac{\partial \overline{p}}{\partial x_i} + (\nu + \nu_{SGS}) \frac{\partial^2 \overline{u}_i}{\partial x_j \partial x_j} + \lambda \Delta P \delta_{i1} + \alpha g (\overline{\theta} - \theta_0) \delta_{i3} \,. \qquad (1)$$

Resolved-scale variables are denoted by over-bars. Tensor notation and summation convention on repeated indices are used (i, j, k = 1, 2, 3 denote streamwise, spanwise and vertical directions, respectively). u_i are the velocity components, p is the kinematic pressure, ν is the kinematic viscosity, λ = 1 in free-stream layer and λ = 0 inside street canyon, δ_{ij} is the Kronecker delta, α is the thermal expansion coefficient, g is the gravitational acceleration, θ is the temperature, and θ_0 is a reference temperature (mean temperature between the top and bottom boundaries). The eddy viscosity ν_{SGS} is calculated by

$$\nu_{SGS} = C_k k_{SGS}^{1/2} \Delta \qquad (2)$$

where C_k = 0.07 is a modelling constant. The SGS turbulent kinetic energy (TKE) k_{SGS} is calculated by solving the transport equation

$$\frac{\partial k_{SGS}}{\partial t} + \overline{u}_j \frac{\partial k_{SGS}}{\partial x_j} = 2\nu_{SGS} S_{ij} S_{ij} - C_\varepsilon \frac{k_{SGS}^{3/2}}{\Delta} + (\nu + \nu_{SGS}) \frac{\partial^2 k_{SGS}}{\partial x_j \partial x_j} + \frac{\alpha g \nu_{SGS}}{\mathrm{Pr}} \frac{\partial \overline{\theta}}{\partial x_j} \delta_{i3} \qquad (3)$$

where S_{ij} is the strain rate tensor and C_ε = 1.05 is another modelling constant. Both the Prandtl number Pr and the Schmidt number Sc are set to 0.72.

The intensity of unstable stratification is controlled by the magnitude of gravitational acceleration constant g. Using the free-stream layer height H, the free-stream wind velocity U_f and the overall temperature difference $\Delta\theta$ as the characteristic length, velocity and temperature scales, the Reynolds number Re and the bulk Richardson number Ri are in the ranges $40{,}000 < \mathrm{Re} < 100{,}000$ and $-2 < \mathrm{Ri} < 0$, respectively (negative Ri represents unstable thermal stratification). The calculation of LES proceeds until the pseudo steady-state is arrived such that the mean flows and the statistics of velocity fluctuation do not change with time. The LES data are collected for at least ten channels of flow time. Afterward, they are averaged in time and spanwise direction then are analysed to determine the ensemble averaged properties which are denoted by the bracket $\langle \cdot \rangle$.

RESULTS AND DISCUSSION

When the unstable thermal stratification enhances (i.e. Ri increases), the mean streamwise velocity profile in the free-stream layer becomes more uniform (Figure 2). It is mainly due to the enhanced turbulent mixing, which can be observed from the increase in the velocity fluctuations.

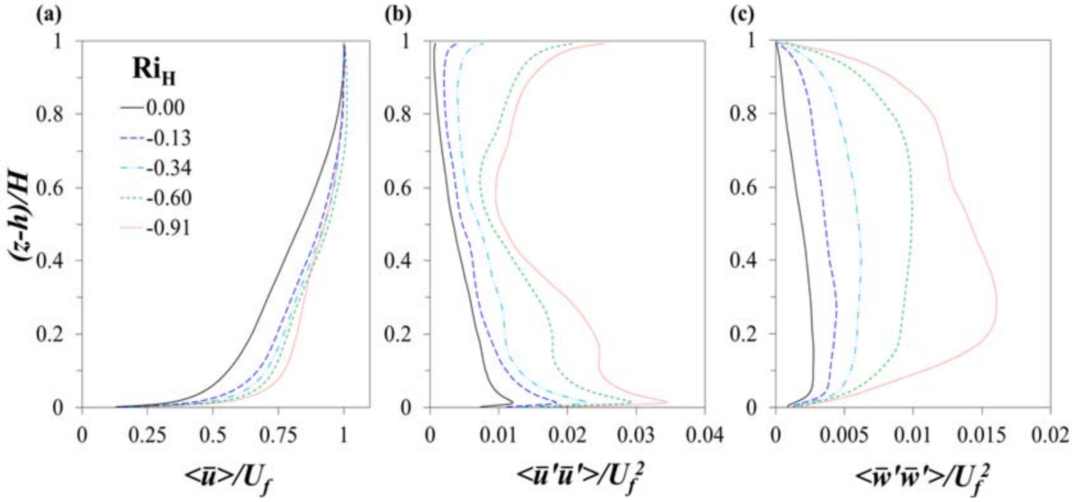

Figure 2. Vertical profiles of (a) streamwsie mean velocity, (b) streamwise velocity fluctuation and (c) vertical velocity fluctuation for h/b = 1 at different bulk Richardson number Ri.

When the streamwise mean velocity is plotted in semi-logarithmic scale with normalization using friction velocity u_τ and viscous length scale δ_v, it is shown that the profile deviates from the isothermal one and the deviation depends on the intensity of (unstable) stratification (Figure 3). The common form of logarithmic law of the wall (log-law) overestimates the wind velocity. The reduction in velocity is due to the increased drag from turbulent mixing.

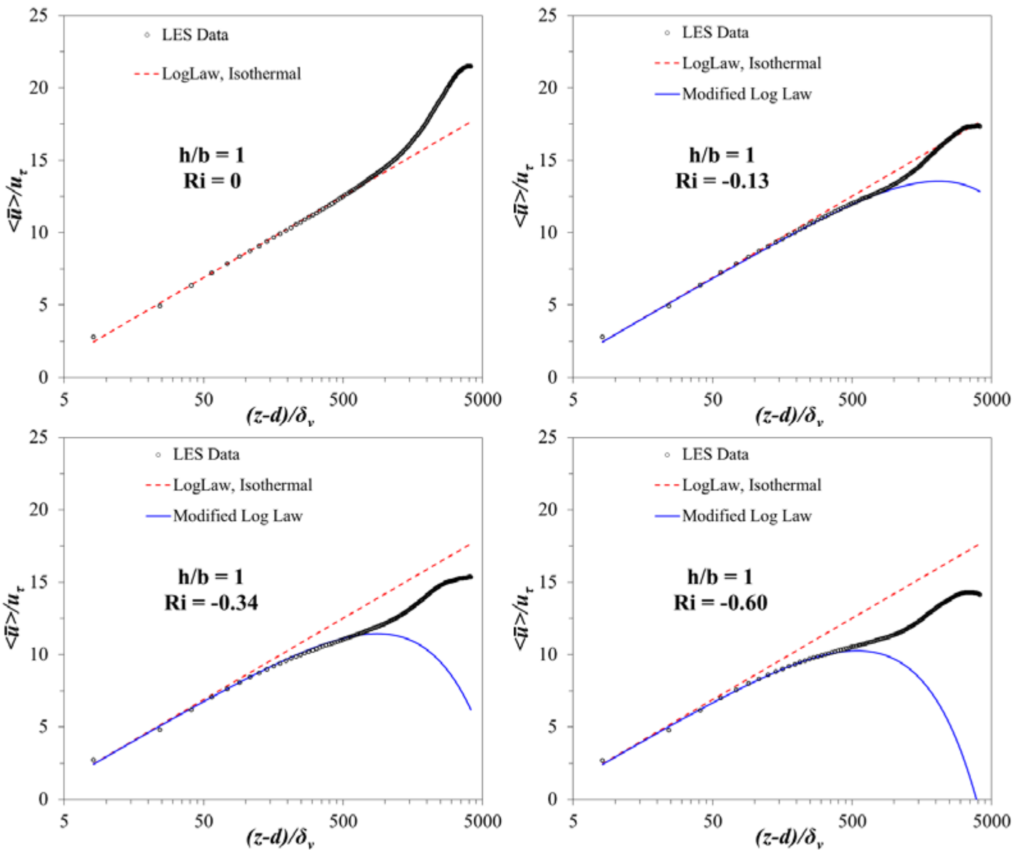

Figure 3. Streamwise mean velocity profile in semi-logarithmic scale for h/b = 1 at different bulk Richardson number Ri.

To account for the deviation, a power series in z/L can be augmented to the log-law (Turner 1979). For slight stratification, only the linear term is retained and the higher order terms can be neglected, whose result is as follow

$$\frac{<u>}{u_\tau} = \frac{1}{\kappa}\left[\ln\frac{z-d}{z_0} + \alpha\frac{z}{L}\right] \tag{4}$$

where κ (= 0.41) is the von Karman constant, d is the displacement height (independent from stratification), z_0 is roughness length (independent from stratification), α (~0.45) is an empirical constant and L is the Monin-Obukov length (negative for unstable stratification with magnitude decreases with decreasing unstable stratification intensity). As shown in Figure 3, it is shown that the LES results match the modified log-law Equation (4) well.

In addition to the wind flow behaviours above the urban roughness discussed previously, the ventilation performance, quantified by air exchange rate (ACH), pollutant exchange rate (PCH), average pollutant concentration in the street canyon and pollutant retention time, and the plume dispersion behaviour above urban roughness in different intensities of stratification will be reported in the conference.

CONCLUSION

A series of LES is employed to study the behaviours of wind flow and pollutant transport inside and above idealized urban street canyons. It is found that the turbulent mixing is stronger in unstable thermal stratification than that in isothermal conditions. With the increase of stratification intensity, the mean velocity profile shows a larger deviation compared with the commonly used log-law. The deviation is successfully accounted by augmenting a linear function of z/L to the common log-law in slightly unstable stratification. The air quality in street canyons improves in unstable thermal stratification, which is indicated by the higher air exchange rate (ACH) and pollutant exchange rate (PCH), lower street canyon average pollutant concentration and pollutant retention time and the faster rate of plume dispersion in free-stream layer as well.

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