Large-eddy simulation of turbulent flows and pollutant transport inside and above idealized urban street canyons under different unstable thermal stratification

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Abstract

Large-eddy simulation (LES) is employed to study the behaviours of flows and pollutant transport inside and over idealized urban street canyons under different unstable thermal stratification. Three configurations of idealized street canyon, consisting of building-height-to-street-width (aspect) ratios, 0.5, 1 and 2, are considered. Under unstable stratification, the vertical profiles of streamwise velocity and temperature over the bottom rough surface are more uniform and the turbulent transport of momentum and heat are enhanced. Inside the street canyons, the ventilation performance, which are characterized by the air exchange rate (ACH), pollutant exchange rate (PCH), pollutant retention time and average pollutant concentration, is found improved in unstable stratification.

1 Introduction

Apart from wind speed, wind direction, building geometry and building size, thermal stratification is another major factor affecting the flows and pollutant transport over urban areas and inside street canyons. This situation is not rare that is usually found in daytime when the solar radiation is strong and the wind is calm, i.e. an environment of unstable thermal stratification. It can be observed from the field measurements that the temperature on a building facade is up to 50 ^{o}C in a summer afternoon (Bourbia and Awbi, 2004) and the temperature gradient in the near-wall region is as large as 5 ^{o}C cm^{-1}, resulting in an over-10-^{o}C temperature difference between building facade and air (Louka et al., 2002). It was also observed that unstable stratification in the urban boundary layer accounted for 85% in daytime and still 64% in night-time (Niachou et al. 2008). Therefore, the effects of unstable thermal stratification on the wind flows and ventilation in urban environments should not be overlooked.

Under unstable thermal stratification, the (negative) vertical temperature gradient induces an upward buoyancy force to the wind fields that substantially changes the mean flows, and the turbulent transport of momentum, heat and pollutants both inside and above urban street canyons. Numerous computational fluid dynamics (CFD) studies have been performed to investigate the turbulent flows and pollutant transport inside a street canyon under different thermal configurations, such as wall heating, ground heating and all-urban-surface heating (Xie et al., 2007, Li et al., 2010, Cheng and Liu, 2011). These studies generally showed that the turbulence is more energetic and the ventilation is promoted in unstable stratification. The changes in turbulence structure due to unstable stratification affect the ground-level ventilation performance of a street canyon, especially the narrow one, in which the mean wind is relatively calm and the pollutant removal mainly relies on roof-level turbulence. Therefore, an in-depth understanding of how unstable thermal stratification affects the behaviours of turbulent flows and pollutant transport inside and above street canyons could facilitate sophisticated urban planning towards better air quality. For example, the thermal environment of a street canyon can be controlled by building materials of proper thermal properties or orientation of building facades with respect to incoming solar radiation such that the ground-level pollutant concentrations are reduced.

In this study, large-eddy simulation (LES) sensitivity tests, including urban geometry configurations of three aspect ratios (0.5, 1 and 2) and different intensities of unstable thermal stratification, are performed with the neutral case for each urban configuration as the respective reference. The LES results are compared to the wind tunnel results by Uehara et al. (2000). For the free-stream region above the building roughness elements, the vertical profiles of mean streamwise velocity, mean temperature, velocity fluctuations, and turbulent momentum and heat fluxes are discussed. Inside the (first) street canyon with the ground-level pollutant source, the pollutant concentrations, ventilation performance (measured by air (ACH) and pollutant (PCH) exchange rates), pollutant retention time and average pollutant concentration under different unstable thermal stratification are also reported.

2 Methodology

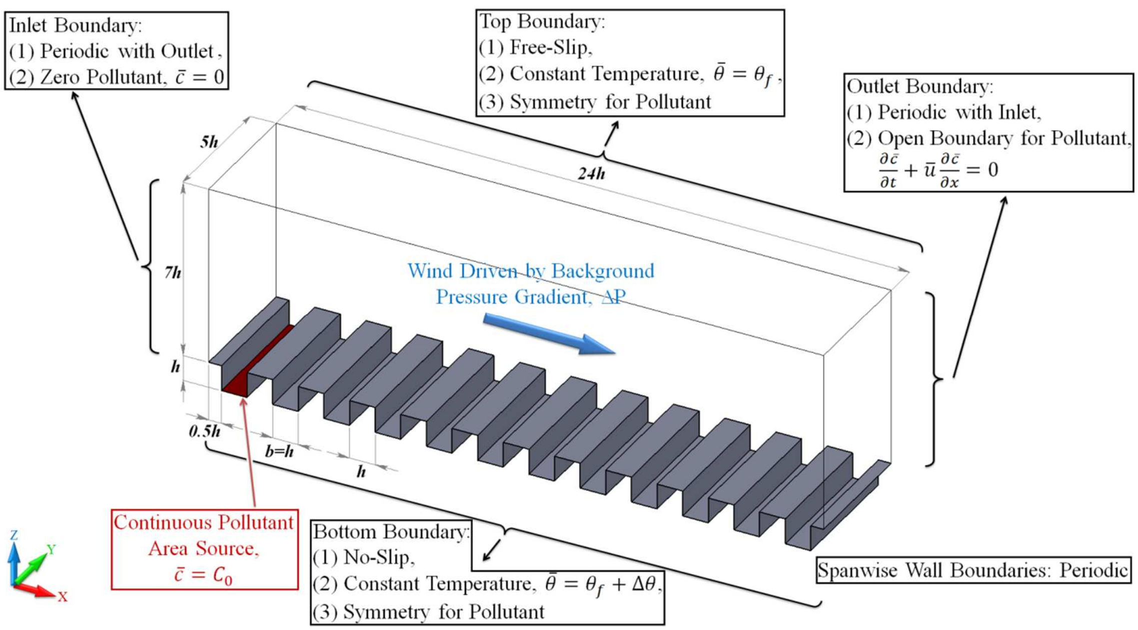

Figure 1: Computational domain and boundary conditions

LES equipped with the one-equation subgrid-scale (SGS) turbulent kinetic energy (TKE) model and the box filter (flow variables are filtered according to the grid size) is employed in this study. A three-dimensional (3D) domain, which is homogeneous in the spanwise direction, is constructed by a series of idealized (rectangular) urban street canyons and a free-stream region aloft (Figure 1). Three values of building-height-to-street-width (aspect) ratios, h/b = 0.5, 1 and 2, are examined and the number of street canyons is 8, 12 and 16, respectively, where h (kept constant) is the building height and b (varied) is the street width. The ratio between the height of free-stream region and the building height H/h equals 7. A uniform background pressure gradient ΔP_x is applied in the streamwise direction to drive the prevailing flow in the free-stream region. Hence, the free-stream wind is perpendicular to the street axes so that the worst scenario of street canyon ventilation is examined. A free-slip boundary condition (BC) is assigned to the domain top while no-slip BCs are assigned to all urban surfaces. To simulate the unstable thermal stratification, the top boundary is kept at constant temperature θ_f while the urban surfaces are kept at a higher constant temperature $\theta_f + \Delta\theta$. Periodic BCs for flows and temperature are assigned to the spanwise and streamwise domain extents simulating infinitely repeating, infinitely long street canyons. Buoyancy force is modelled by the Boussinesq approximation so that the effects of density variation are neglected except in the buoyancy force in the governing equations. The intensity of unstable thermal stratification is controlled by the value of gravitational acceleration g, with $g = 0$ for the reference cases in neutral stratification.

An area source of constant concentration C_0 is used to release pollutant continuously on the ground surface of the first street canyon. A zero-pollutant BC is assigned to the domain inlet, a symmetry BC to the domain top and the urban surfaces, an open BC to the domain outlet, hence, the pollutant is removed from the domain by prevailing flow without reflection. Periodic BCs are assigned to the spanwise extent. Consequently, in the first street canyon, the ground-level pollutant emission rate equals the vertical pollutant flux across the roof area that determines the streamwise pollutant flux moving out through the domain outlet in pseudo steady-state.

In the LES models, the fluid (air) is assumed to be dry and incompressible while the pollutant is assumed to be passive (flow is independent from pollutant concentration) and inert (no chemical reaction). The resolved-scale parts of wind velocity, temperature, kinematic pressure and pollutant concentration are calculated numerically from the filtered governing equations, namely, the continuity (1), momentum transport (2), thermal energy transport (3) and pollutant transport (4):

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

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

$$\frac{\partial \overline{\theta}}{\partial t} + \overline{u}_j \frac{\partial \overline{\theta}}{\partial x_j} = \frac{(\nu + \nu_{SGS})}{\mathrm{Pr}} \frac{\partial^2 \overline{\theta}}{\partial x_j \partial x_j} \tag{3}$$

$$\frac{\partial \overline{c}}{\partial t} + \overline{u}_j \frac{\partial \overline{c}}{\partial x_j} = \frac{(\nu + \nu_{SGS})}{\mathrm{Sc}} \frac{\partial^2 \overline{c}}{\partial x_j \partial x_j} \tag{4}$$

The over-bar denotes the resolved-scale variables. Tensor notation and summation convention on repeated indices are used (i, j = 1, 2 and 3 denote streamwise x, spanwise y, and vertical z directions, respectively). u_i is the velocity vector, p is the kinematic pressure, $\lambda = 1$ for the free-stream region and $\lambda = 0$ inside the street canyons, δ_{ij} is the Kronecker delta, ν is the kinematic viscosity, α is the thermal expansion coefficient, θ is the temperature, θ_0 is the reference temperature (a nominal mean temperature in the domain), c is the pollutant concentration. The Prandtl number Pr and the Schmidt number Sc are both set to 0.72. The Smagorinsky SGS model (Smagorinsky, 1963) is used and the kinematic eddy viscosity ν_{SGS} is calculated by:

$$\nu_{SGS} = C_k k_{SGS}^{1/2} \Delta \tag{5}$$

where C_k (= 0.07) is a modelling constant and Δ (= $[\Delta x \Delta y \Delta z]^{1/3}$) is the filter width. By the one-equation SGS model (Schumann, 1975), the SGS turbulent kinetic energy (TKE) k_{SGS} is calculated by its transport equation:

$$\frac{\partial k_{SGS}}{\partial t}+\overline{u}_j\frac{\partial k_{SGS}}{\partial x_j}=2\nu_{SGS}S_{ij}S_{ij}-C_\varepsilon\frac{k_{SGS}^{3/2}}{\Delta}+(\nu+\nu_{SGS})\frac{\partial^2 k_{SGS}}{\partial x_j\partial x_j}+\frac{\alpha g\nu_{SGS}}{\Pr}\frac{\partial\overline{\theta}}{\partial x_j}\delta_{j3} \tag{6}$$

where the strain rate tensor S_{ij} is calculated by:

$$S_{ij}=\frac{1}{2}\left(\frac{\partial\overline{u}_i}{\partial x_j}+\frac{\partial\overline{u}_j}{\partial x_i}\right) \tag{7}$$

and C_ε (= 1.05) is another modelling constant.

The spatial domain for each model is discretized into over 4,500,000 rectangular elements. The grid is refined near all the no-slip surfaces to capture the rapidly changing flow variables. The smallest grid sizes in the street canyon and the free-stream region are, respectively, $0.0431\times0.0625\times0.0431h^3$ and $0.0431\times0.0625\times0.0274h^3$. The time step increment for each model is $0.005h/U_f \le \Delta t \le 0.03h/U_f$, where U_f is the free-stream velocity (streamwise velocity at top boundary) depending on the thermal stratification. To achieve the pseudo steady-state, an initialization period of at least $1000h/U_f$ is processed in a coarser mesh (around 500,000 to 600,000 rectangular elements). Afterwards, another development time of at least $50h/U_f$ is processed in the aforementioned (refined) mesh configuration. The data are then collected for another duration of at least $50h/U_f$ that are averaged in the spanwise direction and over the sampling time.

As the simulation time goes on, the fields of turbulent flow, temperature and pollutant are self-developed. The LES data in pseudo steady-state flows, in which the mean and fluctuating statistics are unchanged with time, are ensemble averaged in time and spanwise domains. The calculated statistics are subsequently analysed in different non-dimensional forms.

3 Results and Discussion

The simulation conditions are characterized by the Reynolds number Re and the bulk Richardson number Ri (Table 1). The free-stream velocity U_f and the overall domain temperature difference $\Delta\theta$ are the velocity and temperature scales, respectively. The subscripts h and H denote which length scale is used. Building height h is used as the length scale when describing the flow conditions inside a street canyon while the free-stream height H is used for flow conditions in the free-steam region.

Table 1: Simulation conditions of LES models.

h/b	Re_H	Ri_H	Re_h	Ri_h
0.5	74,000 ↓ 30,000	0 ↓ -7.57	10,600 ↓ 4,300	0 ↓ -1.08
1	89,000 ↓ 42,000	0 ↓ -3.92	12,700 ↓ 6,000	0 ↓ -0.56
2	94,000 ↓ 42,000	0 ↓ -3.80	13,500 ↓ 6,100	0 ↓ -0.54

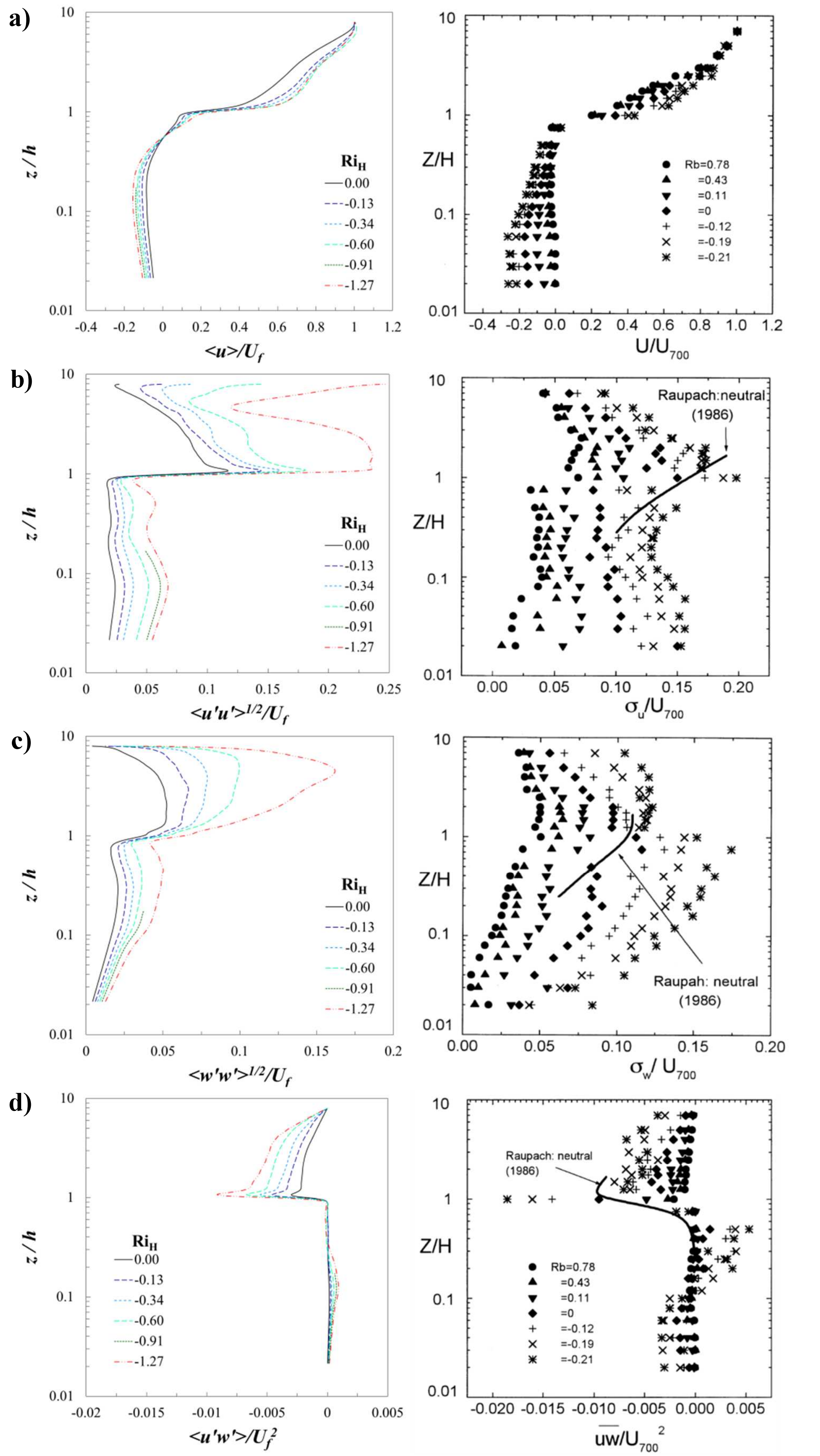

Figure 2: Vertical profiles of a) streamwise mean velocity, b) standard deviations of streamwise velocity, c) standard deviations of vertical velocity and d) Reynolds stress at the middle of street canyon. The LES and wind tunnel results are shown in the left and right panels, respectively

The LES results are compared to those of the wind tunnel experiments of Uehara et al. (2000) at *h/b* = 1. The vertical profiles of mean streamwise wind velocity, the standard deviations of streamwise and vertical wind velocities and the Reynolds stress along the vertical line at the middle of a street canyon are shown in Figure 2. In the wind tunnel experiments, 3D cubical blocks, which were different from the 2D square ribs in the current LES, were used as the building elements. Shorter roughness elements were used to develop an incoming turbulent flow that entered the test section containing the building elements. The vertical profiles were taken at the fifth (sample) street canyon. The Reynolds number *Re* based on building height and incoming flow velocity was about 3,500. The bottom ground surface was heated to induce the unstable stratification and the building elements are thermally insulted. The bulk Richardson number *Ri*, which is used to describe the wind tunnel results, was based on the temperature difference between the ground and the roof-level opening of street canyons. The velocity scale used to normalize the wind tunnel results is the mean streamwise velocity at 700 mm above the ground level and the overall height of wind tunnel test section is 1 m.

Both the LES and wind tunnel results show a similar trend for the mean and fluctuating properties of the flows with respect to the increase in unstable stratification. The mean wind relative to the free-stream wind and the turbulence intensities are enhanced both inside the street canyons and in the free-stream region as the unstable stratification are strengthened. However, the mean wind and turbulence intensities inside the street canyons measured in the wind tunnel experiments are several times higher in magnitudes than those in the LES. The discrepancy is mainly due to the 3D geometry of building elements so additional momentum entrainment is transferred from the street intersections around cubical buildings into the street canyons.

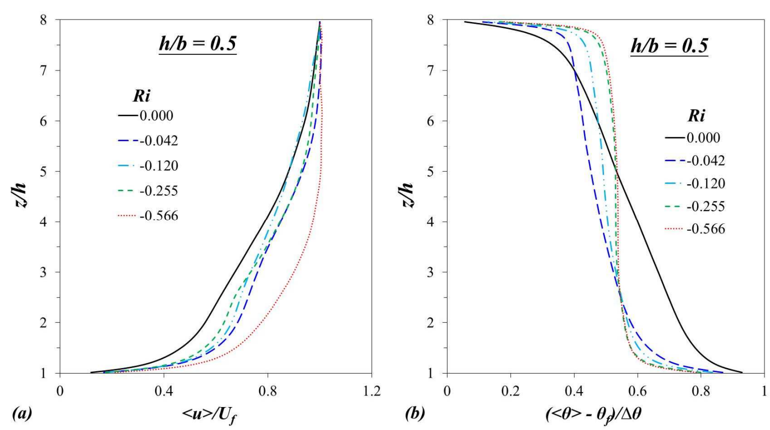

Figure 3: Vertical Profiles of normalized (a) mean streamwise velocity and (b) mean temperature in free-stream region over street canyons of aspect ratio *h/b* = 0.5

In the free-stream region of the models of street canyons of aspect ratio *h/b* = 0.5, by further averaging the LES data in the entire streamwise direction, the vertical profiles of mean flow variables are shown in Figure 3 while the vertical profiles of flow fluctuations, turbulent momentum flux and turbulent heat flux are shown in Figure 4. It is found that, with the increase in buoyancy, the profiles of mean velocity and temperature over urban roughness are more uniform. It is because the turbulent mixing enhances with the level of unstable stratification. The local maximum of turbulence intensity just above the building roof-level rises as the unstable stratification is enhanced. For the LES models of *h/b* = 1 and 2, the trends of results with respective to the level of stratification in the free-stream region are similar to those of *h/b* = 0.5 (which will also be reported in the conference).

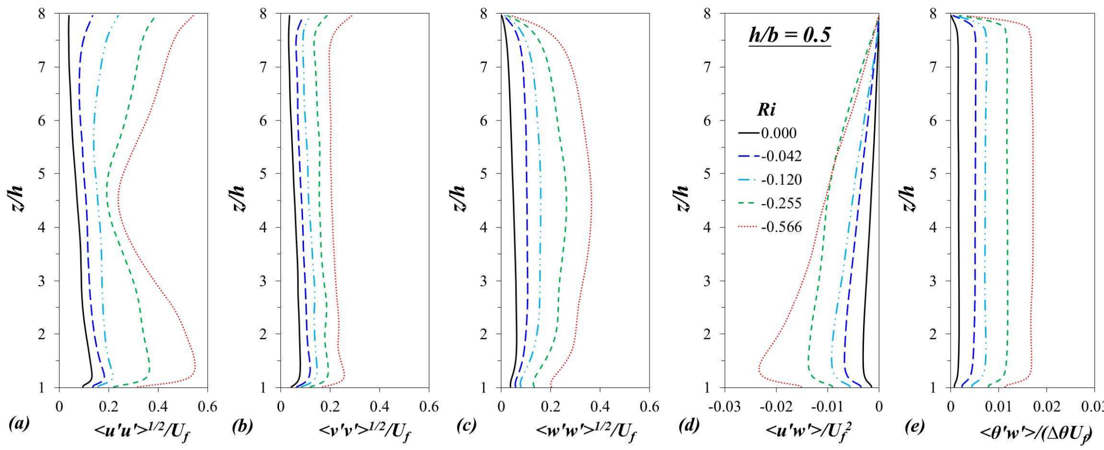

Figure 4: Vertical profiles of normalized (a) streamwise velocity fluctuation, (b) spanwise velocity fluctuation, (c) vertical velocity fluctuation, (d) vertical turbulent momentum flux and (e) vertical turbulent heat flux in free-stream region over street canyons of aspect ratio *h/b* = 0.5

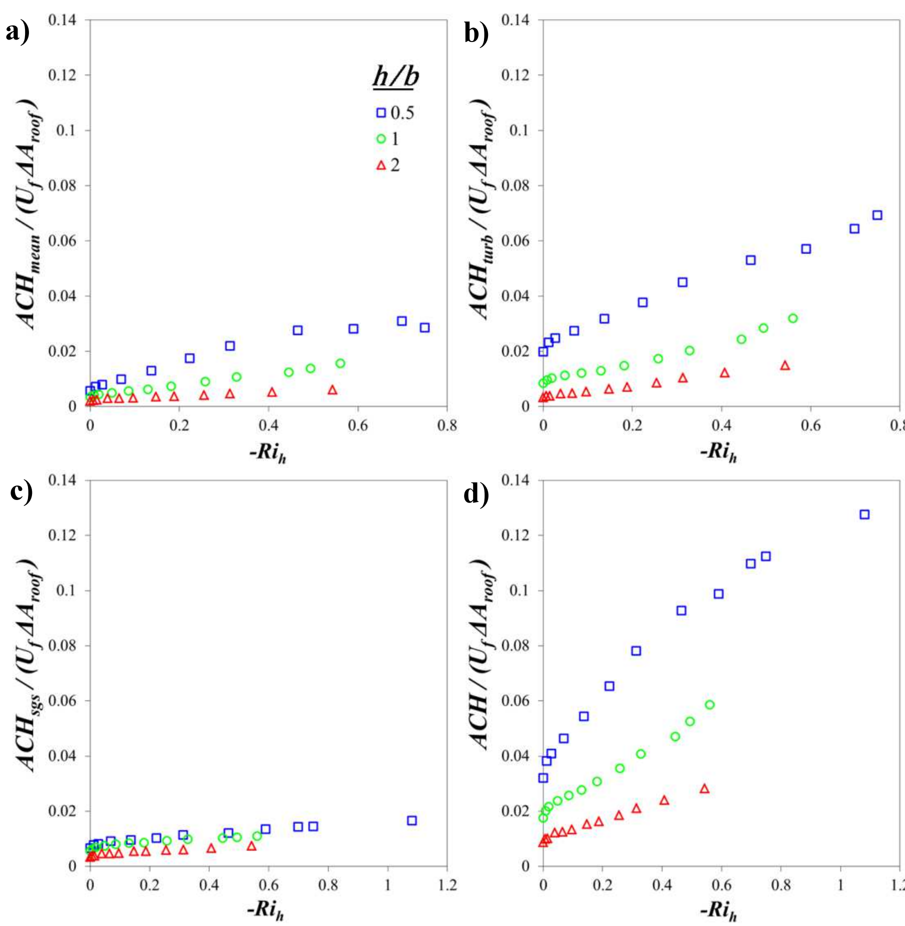

Figure 5. Variation of a) ACH_{mean}, b) ACH_{turb}, c) ACH_{sgs} and d) ACH of street canyons with Ri_h for all ARs

Air exchange rate ACH is defined as the temporal average of the volumetric outflux of air attributed to upward flows at the roof level. ACH is decomposed into ACH_{mean}, ACH_{turb} and ACH_{sgs}, denoting the air volumetric outfluxes driven by upward mean wind velocity, resolved-scale turbulence and SGS turbulence, respectively (Figure 5). The roof-level opening area plus building roof area ΔA_{roof} and the free-stream velocity U_f are used to normalize all the ACH components and ACH. It is shown that the street-canyon ventilation is dominated by turbulence in all the cases (different h/b and Ri_h) and the overall ventilation performance is generally improved with stronger unstable stratification.

Apart from ACH, pollutant exchange rate (PCH), pollutant retention time and average pollutant concentration consistently show that the street-level ventilation performance is improved with stronger unstable thermal stratification (these will also be explained in details in the conference).

4 Conclusions

With unstable thermal stratification, the vertical profiles of mean velocity and temperature in the free-stream region over the roughness elements of hypothetical urban areas are more uniform. Moreover, the velocity fluctuations, turbulent momentum flux and turbulent heat flux are enhanced. Inside the street canyons, ACH, PCH, pollutant retention time and average pollutant concentration all consistently show that the street-level air quality is improved in unstable thermal stratification.

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