HARMO14 - 14th International Conference on
Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes
Kos Island, Greece, October 2 to 6, 2011

Effect of Unstable Thermal Stratification on the Atmospheric Boundary Layer above Urban Street Canyons by Large-Eddy Simulation

W.C. Cheng and Chun-Ho Liu*

Department of Mechanical Engineering, The University of Hong Kong

Pokfulam Road, Hong Kong, China

Parallel Session 8

Urban Scale and Street Canyon Modelling: Meteorology and Air Quality

Correspondence:* **Dr. Chun-Ho LIU
Department of Mechanical Engineering, 7/F Haking Wong Building,
The University of Hong Kong, Pokfulam Road, Hong Kong.
Tel: (852) 2859 7901; *Fax:* (852) 2858 5415; liuchunho@graduate.hku.hk

H14-70: October 4, 2011

Contents

- Introduction
  - Velocity and temperature log profiles
- Methodology
  - LES model and the computational domain
- Results and Discussion
  - Profiles above urban street canyons and the effect of unstable thermal stratifications
- Conclusion

Introduction

- For high-Reynolds-number (Re) flows above idealized homogeneous surface, the wind profile can be described by the law of the wall (Spalding 1962)

- Wall units (u^+, z^+) were suggested to normalize the velocity (u) and wall distance (z) as

$$u^+ = \frac{u}{u_*} \qquad z^+ = z\frac{u_*}{\nu}$$

- Near the wall, three characteristic layers of the wind profiles are suggested
  - Laminar sublayer,
  - Buffer layer, and
  - Log-law region

- In the laminar sublayer (approximately $z^+ < 5$), the velocity is directly proportional to the wall distance as

$$u^+ = z^+$$

- In the log-law region (approximately $z^+ > 30$),

$$u^+ = A_u \ln\left(z^+\right) + B_u$$

- A_u and B_u are constants

- In the buffer region, the velocity profile exhibits a behavior between those in the laminar sublayer and the log-law region

- Similarly, the temperature profile can be approximated by the logarithmic form as

$$\theta^{+} = A_{\theta} \ln\left(z^{+}\right) + B_{\theta}$$

- where θ^{+} (=θ/θ_{*}) is the temperature in wall unit with θ_{*} = ($\partial\theta/\partial z|_{\text{wall}}/u_{*}$) the friction temperature, and A_{θ} and B_{θ} are constants

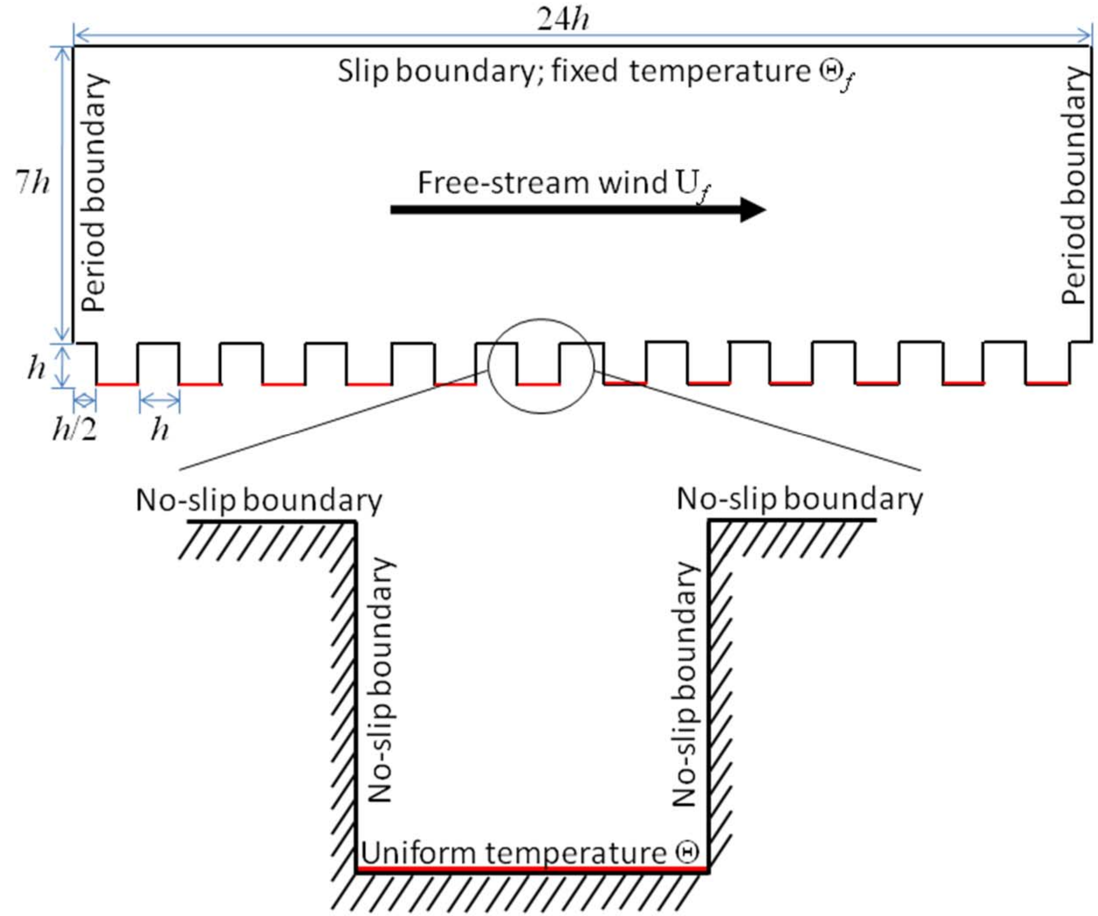
- In this study, we investigate how the log profiles of wind and temperature above urban street canyon change with unstable thermal stratifications

Methodology

- Large-eddy simulation (LES) using open-source CFD code OpenFOAM (OpenFOAM 2011)

- One-equation subgrid-scale (SGS) model (Schuman 1975)

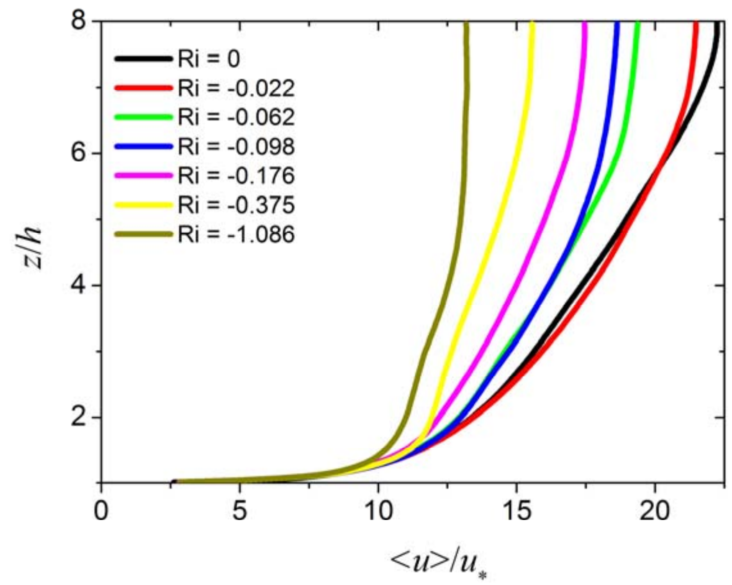
- The domain dimensions are $24h \times 5h \times 8h$. Twelve identical street canyons are considered in order to capture the large-scale turbulence over the buildings in the urban atmospheric boundary layer.

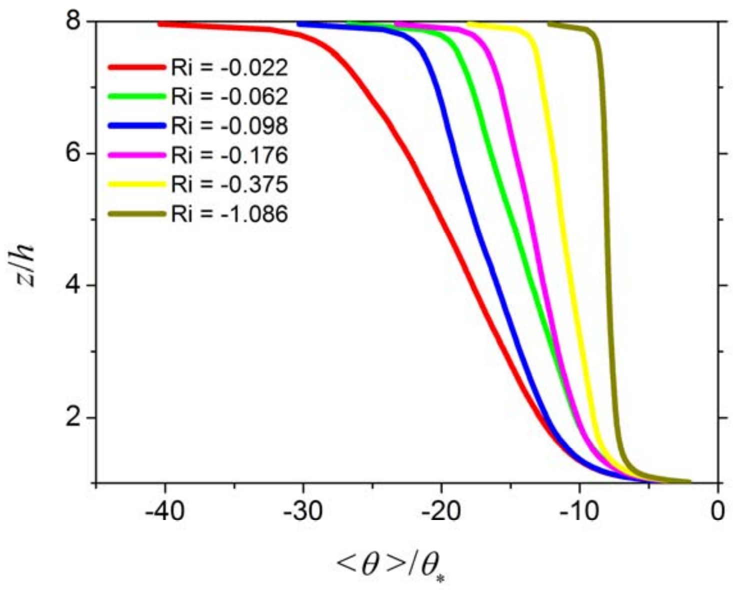


- Re (= $U_f h/\nu$) is about 10,000
- Richardson number
  - Ri (= $\alpha g L(\Theta-\Theta_f)/U_f^2$) is equal to 0, -0.022, -0.062, -0.098, 0.176, -0.375, and -1.086
- LES domain is discretized into 2.4 million of brick elements with grid spacing $1.4\times10^{-2}h$ and $4\times10^{-1}h$ at the bottom and top boundaries, respectively
- After $200h/U_f$ of transient calculation, the results are ensemble averaged (denoted by $<\bullet>$) using another $200h/U_f$ of LES data at time interval $0.1h/U_f$
- Detailed model validation and comparison were reported in Cheng and Liu (2011a) and (b).

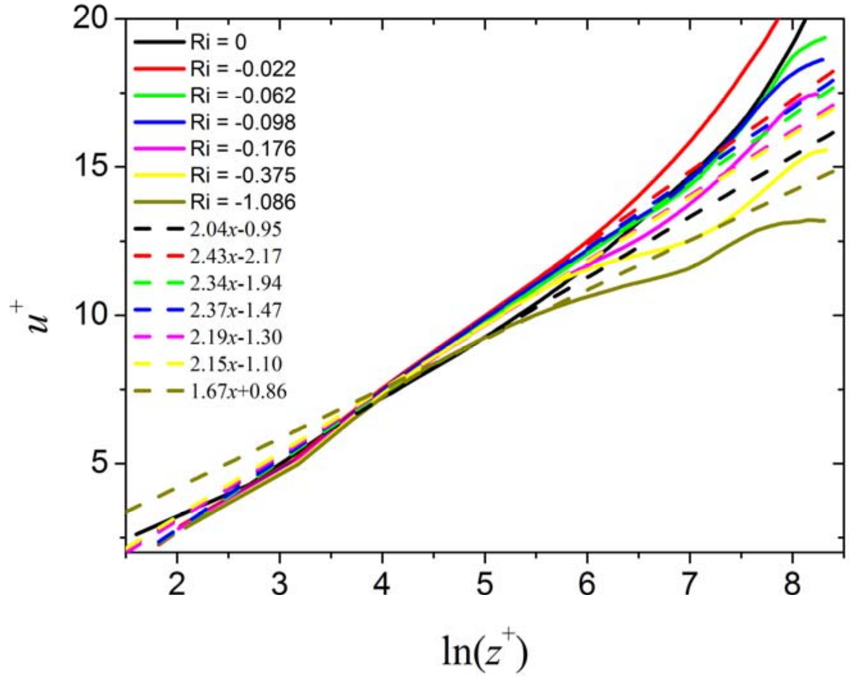
Results and Discussion

- Substantially modifications in the vertical profiles of wind and temperature above the street canyons at different Ri are observed



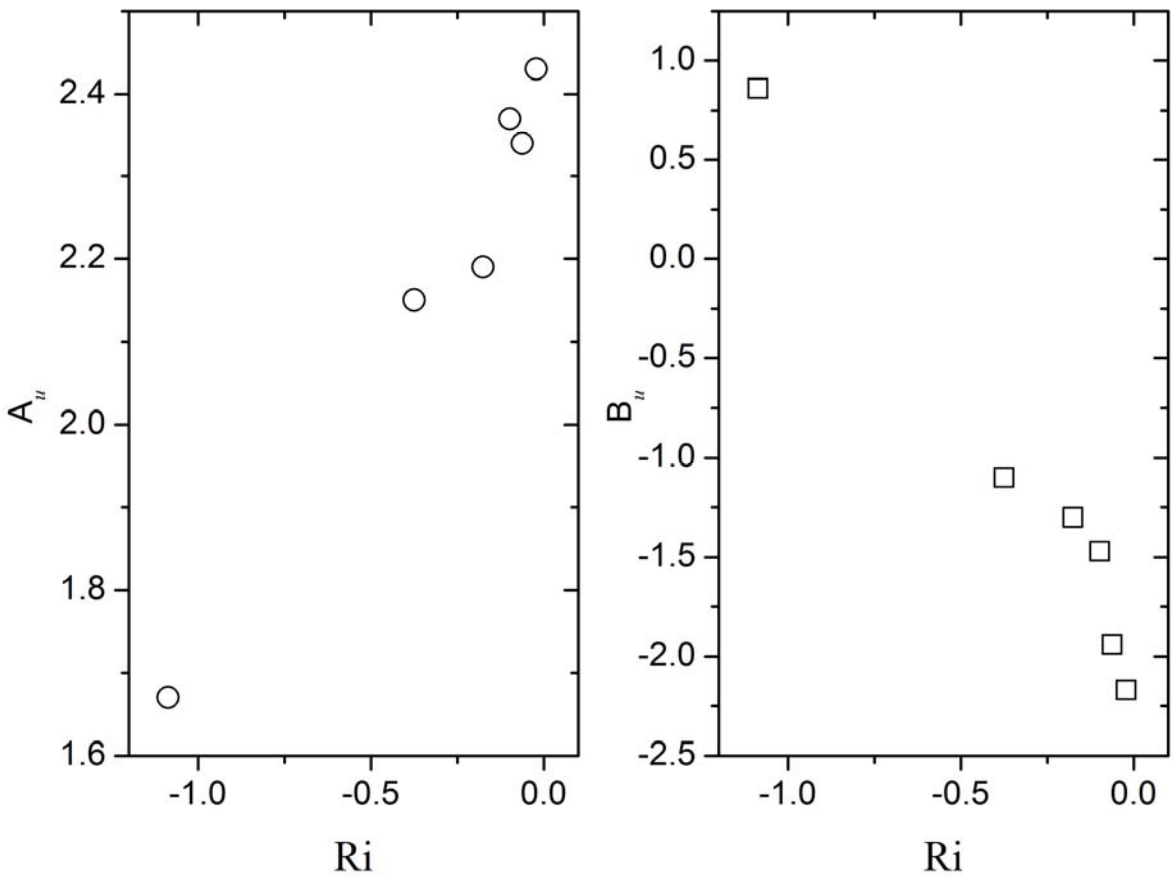


- Velocity in wall unit (u^+) against z^+ at different Ri
- Boundary layer is in fact developed over the street canyons therefore vertical displacement height of h is employed
- The slope of the curves in general decreases with decreasing Ri. The profiles fall onto a straight line at $50 < z^+ < 300$, which correspond to the logarithmic profile

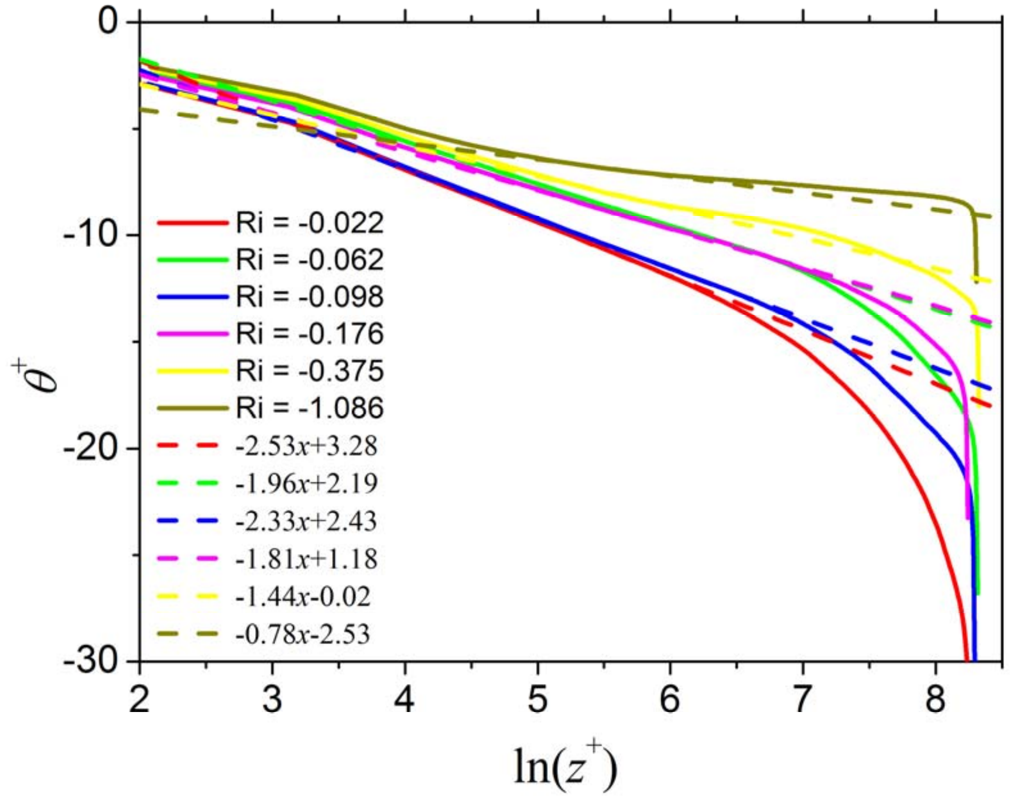


- As Ri increases from -1 to 0, A_u increases from 1.7 to 2.4 while B_u decreases from 0.7 to -2.2.

$$u^+ = A_u \ln(z^+) + B_u$$

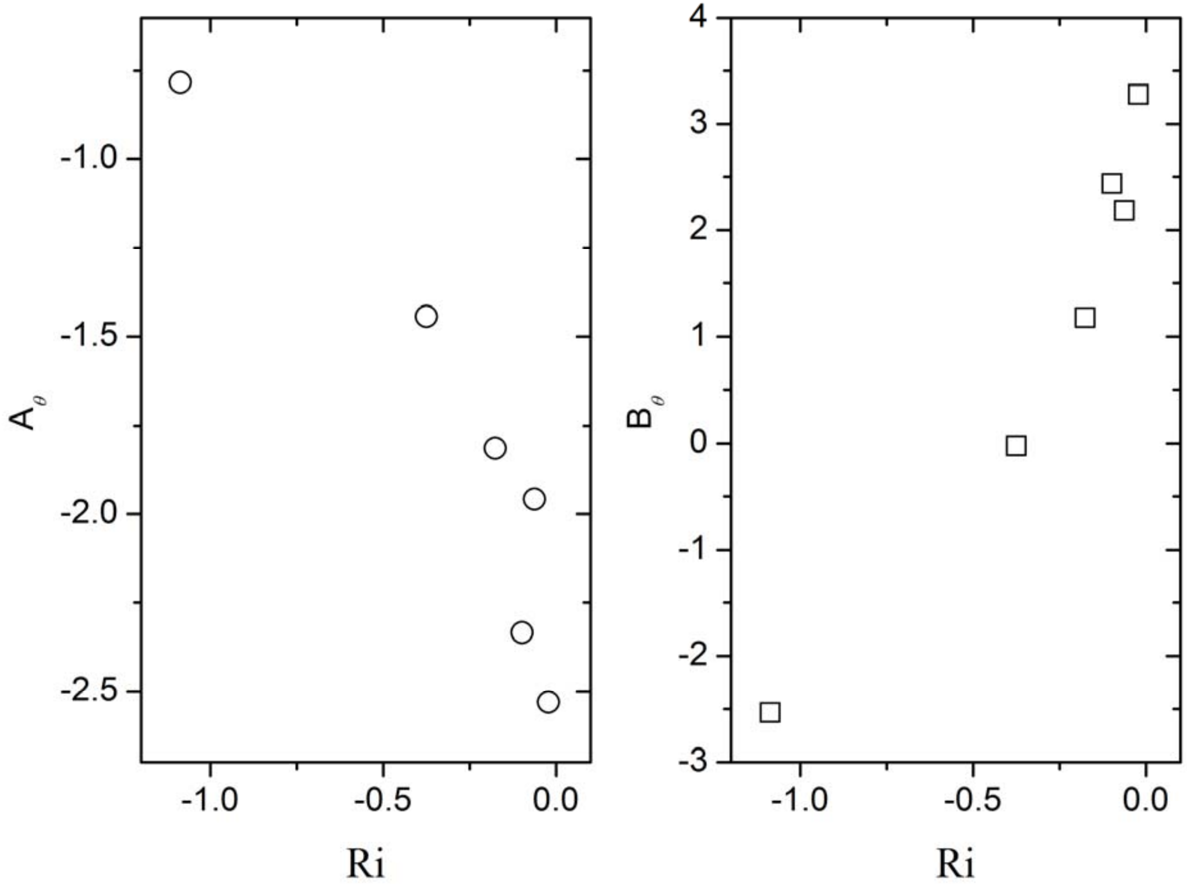


- Temperature (θ^{+}) against ln(z^{+})
- The slope of the curves increases with decreasing Ri that become less negative
- Good least-square fittings are obtained in the range about 150 < z^{+} < 300



- Moving toward neutral stratification for increasing Ri from -1 to 0, the values of A_θ decrease from -0.8 to -2.5 while the values of B_θ increase from -2.5 to 3.

$$\theta^{+} = A_\theta \ln\left(z^{+}\right) + B_\theta$$



Conclusion

- Seven sets of LES are performed to investigate the effect of unstable thermal stratifications on the behaviours of wind and temperature above idealized 2D urban street canyons
- The wind and temperature profiles in unstable stratification can be described by logarithmic profiles in which the slope and y-intercept are functions of thermal stratification
- As Ri decreases from 0 to -1 (more unstable), A_u and B_θ decrease while A_θ and B_u increase
- Changes in A_u and A_θ are due to the enhanced momentum exchange and heat transfer in the turbulent boundary layer

References

W. C., Cheng and C.-H, Liu, 2011a: Large-eddy simulation of flow and pollutant transports in and above two-dimensional idealized street canyons. *Boundary-Layer Meteorol.*, **129**, 411-437.

W. C., Cheng and C.-H., Liu, 2011b: Large-eddy simulation of turbulent transports in urban street canyons in different thermal stabilities. J. Wind. Eng. Ind. Aerodyn., **99**, 434-442.

OpenFOAM 2011: http://www.opencfd.co.uk/openfoam/.

U., Schumann 1975: Subgrid scale model for finite difference simulations of turbulent flows in plane channels and annuli. J. Comput. Phys., **18**: 376-404.

D. B., Spalding 1962: A new analytical expression for the drag of a flat plane valid for both the turbulent and laminar regimes. Int. J. Heat Mass Transf., **5**, 1133-1138.