H14-70

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, Hong Kong

Abstract: The atmospheric boundary layer (ABL) above urban street canyons is investigated to study the role of thermal stratification on the ABL dynamics. Previous studies of the urban atmospheric boundary layer (UABL) mainly treat the roughness elements using surface parameterizations rather than explicitly resolving the building geometry. This approach, however, often overlooks the contribution from building impingement and wake to turbulence production and transport. As such, the current study is aimed to calculate the turbulence in the lower UABL in details in which the urban street canyon geometry is explicitly resolved. The large-eddy simulation (LES) with Boussinesq approximation is used to simulate the unstable thermal stratification of the UABL. The one-equation subgrid-scale (SGS) model is employed to model the SGS turbulence. Twelve street canyons of unity aspect ratio are regularly aligned in the bottom of the computational domain. A uniform temperature, which is higher than that of the ABL, is prescribed at the building roofs, building facades, and streets to model the unstably stratified UABL. Using wall units (friction velocity and friction temperature) properly, it is found that both the velocity and temperature profiles in unstable stratification can be described by the logarithm law, which is well established for flows over rough surfaces. Different from their counterparts in isothermal conditions, the slope and *y*-intercept of the logarithmic profiles depend on the level of thermal stratifications.

Key words: *Large-eddy simulation; logarithm profile; street canyon; thermal stratification; urban roughness.*

INTRODUCTION

For high Reynolds number flows above idealized homogeneous surface, (normalized) wind profile can be well described by the law of wall (Spalding 1962), which has been used in the development of wall model (Launder and Spalding 1974) in various numerical simulations of boundary layer flows. The velocity u and wall-normal distance z are expressed in wall units

$$u^{+} = \frac{u}{u_{*}} \tag{1}$$

and

$$z^{+} = z\frac{u_{*}}{\nu}, \tag{2}$$

respectively, where u_* is the friction velocity and ν is the kinematic viscosity. In the inner layers, the wind profile exhibits different behaviors in different layers, namely the laminar sublayer, buffer zone, and the log-law region. In the laminar sublayer (approximately $z^+ < 5$),

$$u^{+} = z^{+}. \tag{3}$$

While in the log-law region (approximately $z^+ > 30$)

$$u^{+} = A_u \ln(z^{+}) + B_u \tag{4}$$

where A_u and B_u are constants. For aerodynamically smooth surface, $A_u = 1/\kappa = 2.5$ and $B_u = 5.5$ where κ (= 0.4) is the von Kármán constant. In the buffer zone, the velocity profiles exhibit a behavior between those in the laminar sublayer and the log-law region. Similarly, the temperature profile can be approximated logarithmic form as follows

$$\theta^{+} = A_\theta \ln(z^{+}) + B_\theta \tag{5}$$

where θ^+ (=θ/θ_*) is the temperature, $\theta_* = (\partial\theta/\partial z|_{\text{wall}}/u_*)$ the friction temperature, and A_θ and B_θ are constants. In this study, the velocity and temperature profiles, which are assumed to be logarithmic, over repeated 2D street canyons of unity aspect ratio are examined. We attempt to investigate how the (unstable) thermal stratification modifies the wind and temperature profiles in the UABL over idealized urban areas. In particular, how the values of the constants A_u, B_u, A_θ, and B_θ respond to the thermal stratifications are studied. The findings will be useful for the parameterizations of the urban fabrics.

METHODLOGY

High resolution large-eddy simulations (LES) are performed to calculate the wind and temperature profiles above 2D street canyons in different thermal stratifications. The governing equations consist of continuity, and the conservation of momentum and energy. The flow is assumed to be incompressible and Boussinesq approximation is used to model the buoyancy force. The one-equation subgrid-scale (SGS) model (Schumann 1975) is used in which the transport equation of SGS turbulent kinetic energy (TKE) is solved alongside. The LES is performed by the open-source computational fluid dynamics (CFD) code OpenFOAM 1.7 (OpenFOAM 2011). The domain comprises twelve idealized 2D street canyons which are regularly aligned at the bottom. The vertical (*x*-*z*) plane of the computational domain is shown in Figure 1 where *x* is streamwise direction and *z* the vertical direction. A cyclic boundary is applied along the horizontal extent for all the flow variables that represents infinite number of infinitely long street canyons in cross flow. The domain dimension is $24h \times 5h \times 8h$. A couple of street canyons are considered in order to capture the large-scale turbulence over the buildings in the UABL.

The streets, and building facades and roofs are solid no-slip walls. The domain top is a slip wall. Uniform temperature (Θ) is prescribed on the street surfaces, representing solar heat dissipation. Temperature Θ_f, which is lower than that on the streets, is applied at the top boundary to setup an unstable stratification across the domain. Similar models have been previously used. Detailed model validation and comparison were reported in in Cheng and Liu (2011a) and (b). In the current study, the entire LES domain is discretized into 2.4 million of brick elements with grid spacing $1.4\times10^{-2}\ h$ and $4\times10^{-4}\ h$ at the bottom and top boundaries, respectively.

A series of LES of different unstable thermal stratifications are performed. The free-stream wind is driven by a large-scale pressure difference (ΔP) in the momentum equation that is mildly modified by the buoyancy over the street canyons due to the ground heating. The LES is initiated from isothermal conditions with a uniform temperature at the domain bottom. After 200 h/U_f of transient calculation, the results are ensemble averaged (denoted by $\langle\cdot\rangle$) using another 200 h/U_f of LES data at time interval 0.1 h/U_f. Simulation results at Reynolds number Re (= $U_f h/\nu$) equal to 10,000 and Richardson number Ri = $\alpha g L(\Theta - \Theta_f)/U_f^2$) equal to 0, -0.022, -0.062, -0.098, 0.176, -0.375, and -1.086 are reported in this paper where α is the thermal expansion coefficient, *g* the gravitational acceleration, and L = 8*h* is the domain height.

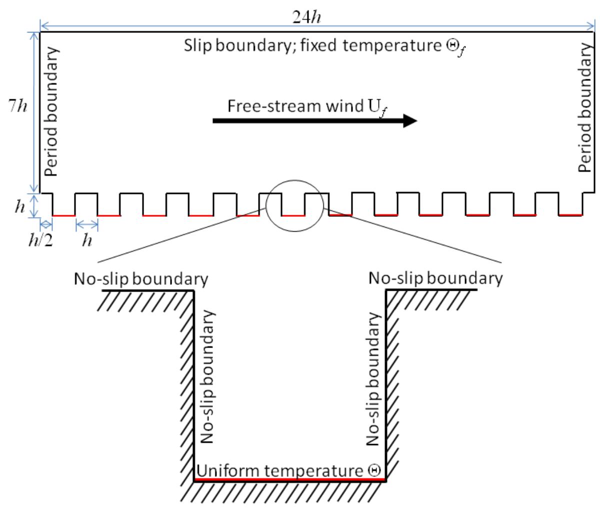

Figure 1. Computational domain.

RESULTS AND DISCUSSION

Substantially modifications in the vertical profiles of wind and temperature above the street canyons at different Ri are observed (Figure 2). The friction velocity (u_*) and temperature (θ_*) are used in the normalization of velocity and temperature, respectively. With decreasing Ri (more unstable), $\langle u\rangle/u_*$ at the top boundary decreases from about 22 to 13.The decreasing $\langle u\rangle$-to-u_* ratio implies a more effective momentum exchange in unstable stratification. Simultaneously, the temperature gradient significantly decreases with decreasing Ri because of the thorough vertical heat transfer in unstable stratification.

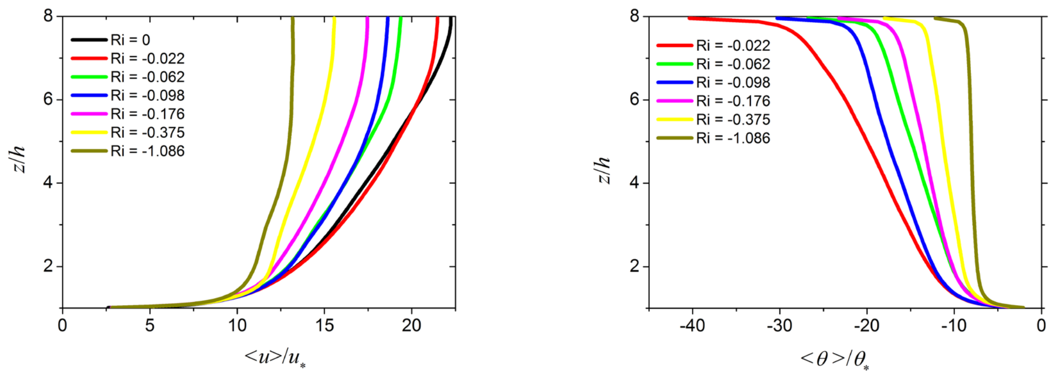

Figure 2. Vertical profiles of mean wind and temperature.

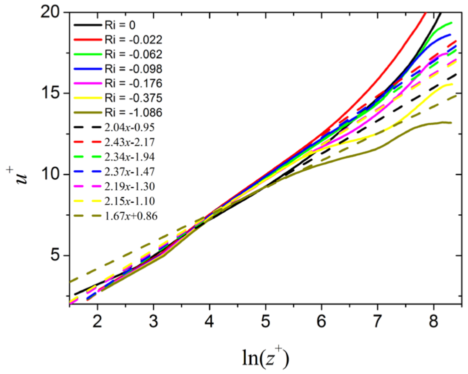

Figure 3. Mean velocity plotted against natural log of wall-normal distance in wall units.

The velocity in wall unit (u^+) against z^+ at different Ri are shown in Figure 3. A vertical displacement of h is used, hence, the boundary layer is in fact developed over the street canyons. 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 (Equation 4). Linear regressions are applied to the LES results that are denoted by the dashed lines in Figure 3. The slope (i.e. A_u) and the y-intercept (i.e. B_u) in different thermal stratification are determined, which are plotted against Ri (Figure 4). 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. The results therefore suggest that unstable thermal stratification affects the logarithmic wind profile over urban street canyons.

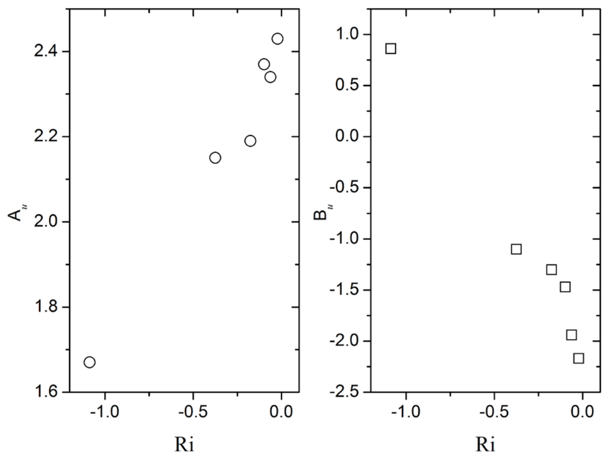

Figure 4. Dependence of A_u and B_u on Ri.

Similarly, the temperature (θ^+) is plotted against $\ln(z^+)$ in Figure 5. While Ri decreases, the slope of the curves increases, becoming less negative. Good least-square fittings are obtained in the range about $150 < z^+ < 300$ in order to determine the values of A_θ and B_θ (Figure 6) in Equation (5). Moving toward neutral stratification for increasing Ri from -1 to 0, the values of A_θ decreases from -0.8 to -2.5 while the values of B_θ increases from -2.5 to 3. This finding in turn suggests that the logarithmic temperature profile above urban street canyons is also modified by the unstable thermal stratifications.

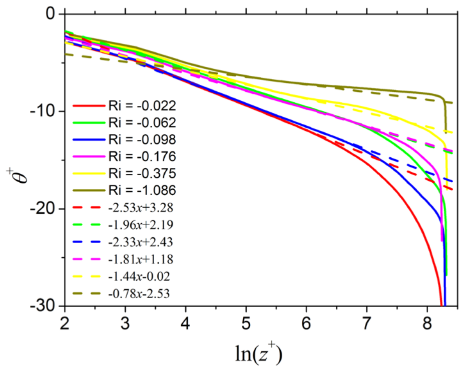

Figure 5. Temperature against nature log of distance from wall in wall units.

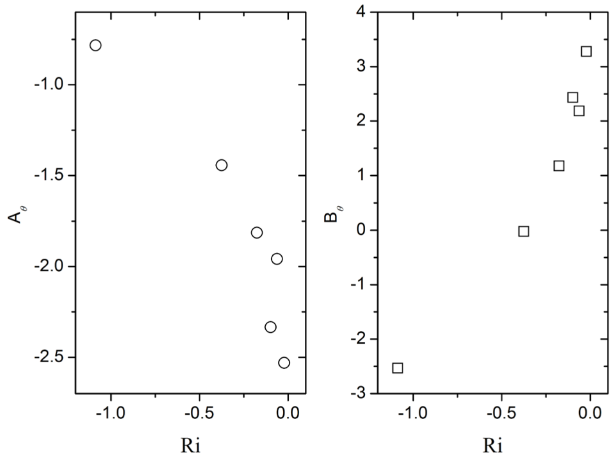

Figure 6. Dependence of A_θ and B_θ on Ri.

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. More effective momentum exchange and heat transfer are observed in unstable stratification. It is found that, similar to their isothermal counterparts, the wind and temperature profiles in unstable stratification can be described by logarithmic profiles Equations (4) and (6) with minor modifications of the slope and *y*-intercept as 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. The changes in A_u and A_θ are caused by the more effective 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.

B. E., Launder and D. B., Spalding 1974: The numerical computation of turbulent flows. Comput. Methods Appl. Mech. Eng., **3**,269-289.

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.