Impact of Stably Stratified Boundary Layers on Tall Building Wake

Abhishek Mishra[1], Matteo Carpentieri[1], Alan Robins[1], Marco Placidi[1*]
[1] Centre for Aerodynamics and Environmental Flow, University of Surrey
Guildford, UK, GU2 7XH
[*] E-mail: m.placidi@surrey.ac.uk

1 INTRODUCTION

Tall building clusters are becoming an essential feature of urban areas. These tall buildings disturb the mass, momentum and heat exchange between the urban environment and the atmosphere [1], significantly affecting pedestrian wind comfort, local and macro-scale surface temperature, and pollutant dispersion [2-4]. The wake behind a cluster of tall buildings exhibits different flow behaviour, with near wake dominated by the building geometry, uniformly advected wake in the transition-wake region, and a global wake similar to that of a single building in the far-wake region [5].

Thermally-stratified flows are ubiquitous in the atmospheric flows. Most of the studies on this topic in the literature have focussed on convective conditions, as modelling of stably stratified cases becomes difficult because of intermittent turbulence, the limited size of the turbulent eddies and the generation of the gravity waves [6]. Stable stratification, although less frequently represented in the literature, is equally important in the atmosphere. Wind tunnel studies on urban arrays have shown that stable stratification leads to a reduction in Reynolds stresses, both inside and above the canopy [7]. The measurement of dispersion characteristics within and above a rectangular array of buildings aligned at 45^o to the wind direction has shown that the mean concentration inside the canopy for the stably stratified case can be twice that for the neutral case [8]. Numerical investigations of the effect of thermal stratification on flow over an urban canopy have found that there is a reduction in the drag and heat transfer coefficient as the flow characteristics change from thermally unstable to stable [9]. Study of stratified flow around a building is very limited, however under strong stratification the wake region of a single building is observed to increase [10].

Most of the stably-stratified flow studies have been focused on modelling the urban canopy layer. The study of the building wake is mostly limited to numerical work. The present study aims to understand the characteristics of the wake flows of a tall building exposed to neutral and stable atmospheric flow conditions using laboratory experiments.

2 METHODS

Wind tunnel experiments for the present study have been carried out in the EnFlo wind tunnel facility located at the University of Surrey. The tunnel's test section is 20 m long, 3.5 m wide and 1.5 m high, with a maximum inlet speed of 5 m/s. To attain the vertical thermal gradient, the inlet section is equipped with 15 power heaters stacked vertically. The power heaters are controlled independently so that the desired temperature profile can be achieved. The floor of the tunnel is cooled using recirculating chilled water and a positive vertical temperature gradient was imposed at the tunnel inlet to simulate stable stratification. A set of 7 Irwin spires of height 986 mm were used at the tunnel inlet to produce the boundary layer height (δ) of 1 m at $x = 14$ m from the inlet, where the building is placed for the measurement (Fig 1). The temperature difference between the floor (θ_{floor}) and the freestream flow (θ_{ref}) was kept to 16 °C. The freestream velocities for neutral and stable cases were 2 m/s and 1.25 m/s, respectively. For the stably stratified case, the bulk Richardson number (Ri_δ) based on quantities at the boundary layer edge ($\delta = 1$ m) was approximately 0.23. The 3 components of velocity were measured using 3D laser Doppler anemometry in the streamwise (x), lateral (y) and vertical (z) directions in the wake of a building which is 60 mm in width (W_A), and 240 mm in height (H_B). The origin of the coordinate system was taken at the centre of the building onto the tunnel's floor, as shown in Fig 1. The vertical profiles were taken at the building centreline ($y = 0$).

DOI 10.5258/WES/P0054

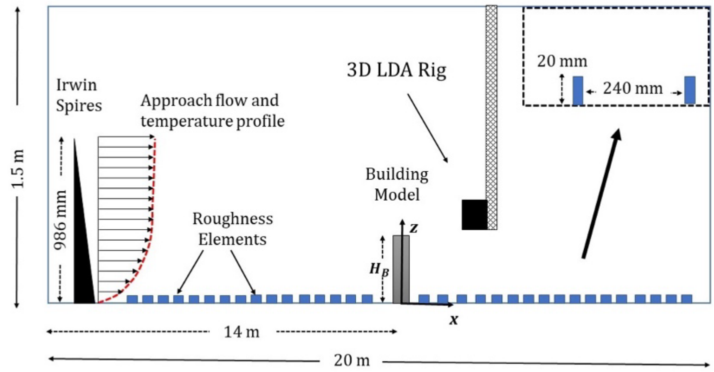


Figure 1: Schematic of the Enflo Wind Tunnel with the relative placement of Irwin spires, roughness elements, and building model.

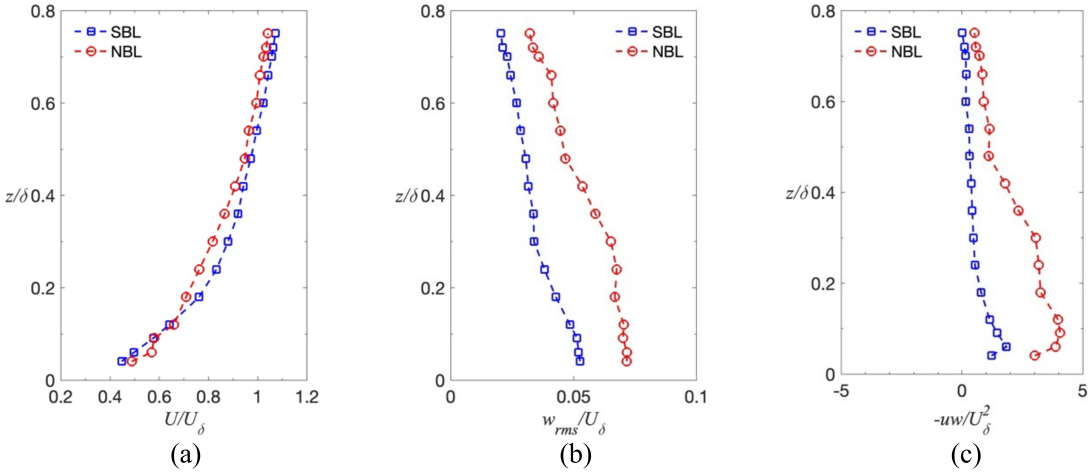
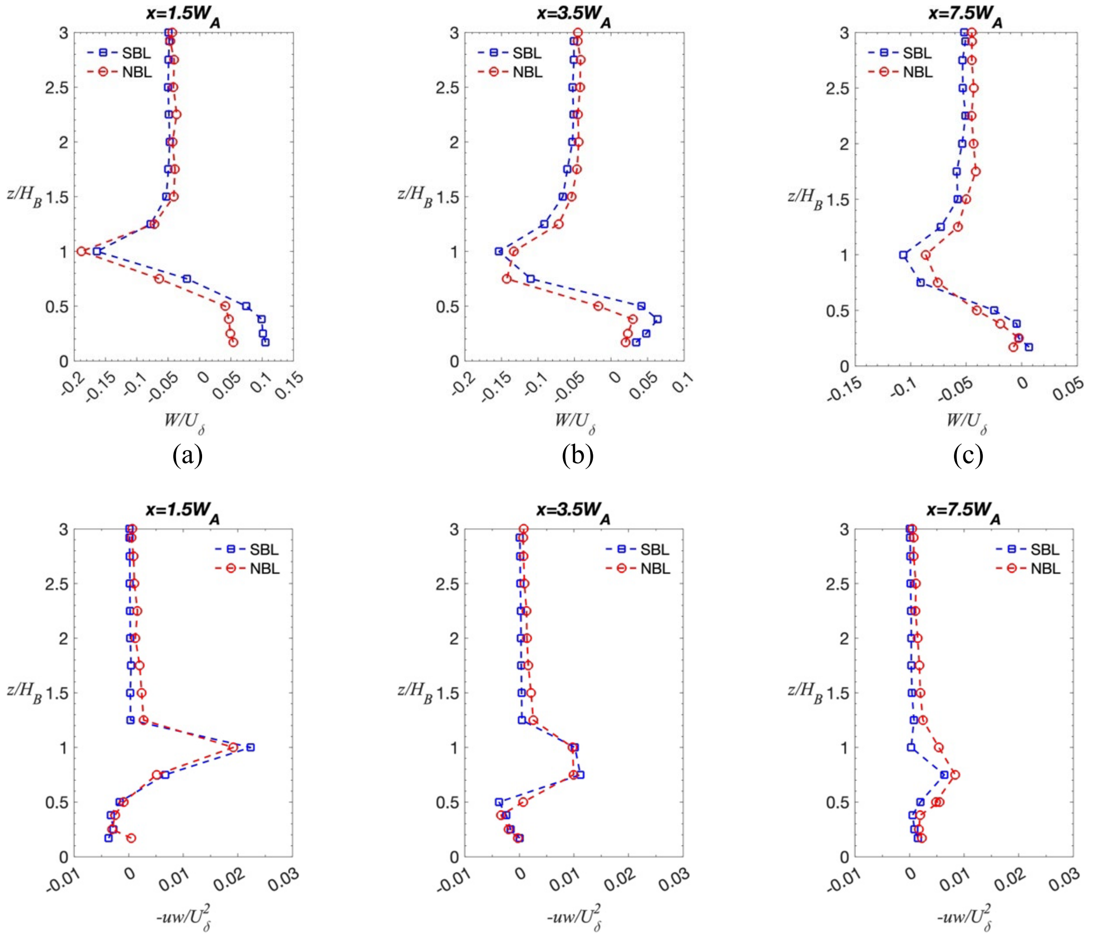


Figure 2: Comparison of flow characteristics between neutral and stably stratified boundary layer upstream of the building, (a) U/U_δ, (b) w_{rms}/U_δ, and (c) $-uw/U_\delta^2$.

3 RESULTS

Fig 2a compares the mean velocity profile, *U,* normalised with the freestream velocity (U_δ) of the approach flow for neutral and weakly-stable flow. The vertical height (*z*) is normalised with δ. The neutral boundary layer (NBL) is observed to be slightly thicker than that of the stable (SBL) flow, as expected. A comparable reduction in the normal stress (w_{rms}) and Reynolds shear stress (*-uw*) is also observed for the stable case (Fig 2b, c). The sharp reduction in the stress components in the weakly-stable case compared to the neutral case highlights the turbulence suppression by the buoyancy effects.

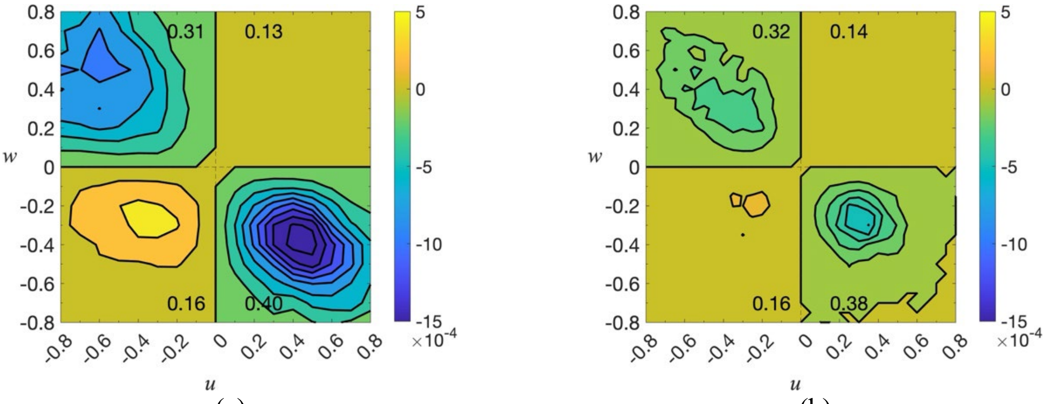
The presence of a building significantly changes the flow characteristics in the wake region for the stably-stratified case. Fig 3 compares the vertical profiles of wall-normal velocity (*W*) and Reynolds shear stress (*-uw*). The wall-normal distance (*z*) is normalised with the building height (H_B). Interestingly, *W* is greater in the SBL than in the NBL up to $x = 3.5W_A$ behind the building, suggesting a higher upwash of the flow from near the ground (Fig 3a and b). This difference subsides for $x = 7.5W_A$ (Fig 3c). For weakly stratified flows, the mechanical turbulence generated by the presence of the building dominates over the suppression caused by the thermal effects. Numerical studies on the effect of stability on the flow around a cubical building have also reported the dominance of shear-generated turbulence for weakly stratified flows [11]. This behaviour is better illustrated by the Reynolds shear stress variation along different



(a) (b) (c)

(d) (e) (f)

Figure 3: Comparison of vertical wake profiles of a single building in the neutral and stable boundary layer, W/U_δ (a, b, c) and *$-uw/U_\delta^2$ (d, e, f).*



(a) (b)

Figure 4: Weighted joint probability distribution function, $uwP(u,w)$, at z=H_B and x = 1.5W_A in (a) neutral boundary layer, and (b) weakly stable boundary layer.

streamwise locations, as shown in Fig 3d-f, which shed some interesting phenomena occurring in the near- and far-wake regions of the building. At $x = 1.5W_A$ and $3.5W_A$ (Figure 3d, e), the Reynolds shear stress variation is almost identical, further validating the dominance of shear-generated turbulence in this region. A slight difference is discerned at $x = 7.5W_A$ (Figure 3f). The Reynolds shear stress for the stable case is smaller than that of the neutral case in the region $0.5 \leq z/H_B \leq 1.25$, highlighting the increasing dominance of the buoyancy-driven turbulence suppression in the far region of the wake. Note that we do not have the data beyond W_A = 7.5W_A to further validate this.

To understand the relative contribution of ejection and sweep motion in the wake of a single building, the weighted joint distribution function of streamwise and wall-normal velocity fluctuations (u and w, respectively) for both neutral and stable boundary conditions at $z=H_B$ and $x = 1.5W_A$ is plotted in Fig 4. This gives the relative contribution of each quadrant to the total Reynolds shear stress separately [12]. The probability of occurrence of each event is also reported in each quadrant for both cases. It is observed that ejection and sweep events are almost equally dominating in both cases. The sweeps are more dominant than the ejections, highlighting the downwash of the flow towards the ground. However, the pair of u and w that contribute the most to total stress are concentrated in a smaller region for the SBL case (Fig 4b), while they are more scattered for the NBL case (Fig 4a), though their magnitude is higher as discussed in Figure 3.

4 CONCLUSION

In the present study, we experimentally examined the effect of thermally stratified atmospheric flows on the wake characteristics of a single building using 3D laser Doppler anemometry. It was found that in weakly-stable flow, the mechanical turbulence generated due to the presence of a building dominates over the thermal effects in the near region of the wake. Interestingly, the upwash velocity at $x = 1.5W_A$ is increased when the flow is stably stratified. Quadrant analysis has shown that the probability of the downwash of the flow (sweep) is almost equal in both cases, further highlighting the relative dominance of mechanically generated turbulence over the buoyant production.

REFERENCES

[1] Baik, J. J., Park, S. B., & Kim, J. J. (2009). Urban flow and dispersion simulation using a CFD model coupled to a mesoscale model. *Journal of Applied Meteorology and Climatology*, *48*(8), 1667-1681.

[2] Makedonas, A., Carpentieri, M., and Placidi, M. (2021). Urban boundary layers over dense and tall canopies. *Boundary-Layer Meteorology*, 181:73–93.

[3] Fuka, V., Xie, Z.-T., Castro, I. P., Hayden, P., Carpentieri, M., and Robins, A. G. (2018). Scalar fluxes near a tall building in an aligned array of rectangular buildings. *Boundary-layer meteorology*, 167(1):53–76

[4] Lim, H. D., Hertwig, D., Grylls, T., Gough, H., Reeuwijk, M. V., Grimmond, S., & Vanderwel, C. (2022). Pollutant dispersion by tall buildings: laboratory experiments and Large-Eddy Simulation. *Experiments in Fluids*, *63*(6), 92.

[5] Mishra, A., Placidi, M., Carpentieri, M., & Robins, A. (2023). Wake Characterization of Building Clusters Immersed in Deep Boundary Layers. *Boundary-Layer Meteorology*, *189*(1), 163-187.

[6] van Dop, H., & Axelsen, S. (2007). Large eddy simulation of the stable boundary-layer: A retrospect to Nieuwstadt's early work. *Flow, turbulence and combustion*, *79*, 235-249.

[7] Marucci, D., & Carpentieri, M. (2020). Stable and convective boundary-layer flows in an urban array. *Journal of Wind Engineering and Industrial Aerodynamics*, *200*, 104140.

[8] Marucci, D., & Carpentieri, M. (2020). Dispersion in an array of buildings in stable and convective atmospheric conditions. *Atmospheric Environment*, *222*, 117100.

[9] Boppana, V. B. L., Xie, Z. T., & Castro, I. P. (2014). Thermal stratification effects on flow over a generic urban canopy. *Boundary-layer meteorology*, *153*, 141-162.

[10] Liu, Z., Li, W., Shen, L., Han, Y., Zhu, Z., & Hua, X. (2021). Numerical study of stable stratification effects on the wind over simplified tall building models using large-eddy simulations. *Building and Environment*, *193*, 107625.

[11] Zhang, Y. Q., Arya, S. P., & Snyder, W. H. (1996). A comparison of numerical and physical modeling of stable atmospheric flow and dispersion around a cubical building. *Atmospheric Environment*, *30*(8), 1327-1345.

[12] Wallace, J. M. (2016). Quadrant analysis in turbulence research: history and evolution. *Annual Review of Fluid Mechanics*, *48*(1), 131-158.