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Investigation of wind speed profiles in an urban area by a multiple-fan wind tunnel facility

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SUMMARY

This study examines whether conventional power-law representations and their associated variability are adequate for describing urban wind-speed profiles over the Taipei Tech campus. A three-way comparison is conducted by combining long-term LiDAR observations, multiple-fan wind-tunnel experiments, and high-resolution CFD simulations under easterly inflow conditions. The two lidars provide synchronous 10-minute mean profiles up to about 300 m at upstream and on-campus locations, revealing highly disturbed urban boundary layer structures and relatively low power-law exponents, between open-country and small-town exposures. Wind-tunnel measurements at three incident angles (75°, 90°, 105°) show very similar profiles and agree closely with the CFD results, confirming that the terrain category B inflow and roughness treatment in the tunnel adequately reproduces the target urban boundary layer. Overall, the combined evidence indicates that a single power-law exponent can only approximate the mean urban profile, and the coefficient of variation remains non-negligible and requires further systematic characterisation.

Keywords: *Lidar, Multiple-fan wind tunnel, CFD, Atmospheric boundary layer*

1. INTRODUCTION

Understanding the vertical wind-speed profile in dense urban environments is essential for wind-resistant design, yet its representation remains uncertain. In practice, urban boundary layers are often approximated by a power-law profile with a single exponent, implicitly assuming that both the mean profile and its coefficient of variation are sufficiently stable in time. However, in a complex metropolitan setting such as central Taipei, this assumption may not hold due to strong spatial inhomogeneity and non-stationary atmospheric conditions. The present study investigates whether the wind profiles over the National Taipei University of Technology (Taipei Tech) campus can be adequately described by a power law and whether the profile variability is sufficiently stable for design applications. To address these questions, we combine long-term field measurements from two Doppler lidars, controlled experiments in a multiple-fan wind tunnel, and high-resolution CFD simulations of an easterly urban boundary layer over the campus and its upstream fetch.

2. FIELD MEASUREMENT

Two Doppler wind lidars were deployed on the Taipei Tech campus to obtain synchronous vertical profiles of the urban boundary layer flow under easterly winds. The first system, LR-08FS III (Mitsubishi Electric), was installed above the Civil Engineering Building; this instrument has a wavelength of about 1.5–1.6 μm, uses a conical VAD scanning strategy, and can retrieve line-of-sight wind speeds from roughly 30 to 600 m with a typical vertical resolution of 30 m. The second lidar, model Z300, was mounted above the Integrated Science Building. Although the two devices differ in hardware configuration and sampling settings, both rely on the same Doppler-shift principle applied to atmospheric aerosols and yield compatible horizontal wind-speed estimates after VAD processing. For the present study, the two lidars were operated simultaneously to collect

10-minute mean wind-speed profiles up to 300 m above each rooftop, forming paired datasets that characterise the upstream and on-campus flow conditions at the two key locations. Because the retrieval quality is weather-dependent, valid data do not always extend to the maximum height; only height levels with sufficient signal-to-noise ratio were retained in the analysis. These synchronous multi-level profiles serve as the observational basis for evaluating the campus wind environment and validating wind-tunnel and CFD simulations.

(a) LR08 (b) Z300 (c) Campus map for Lidar locations

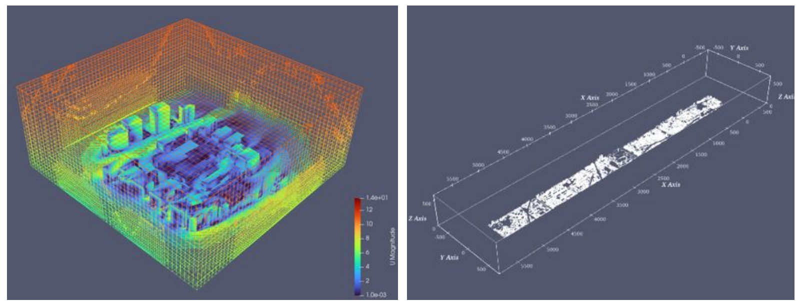
Figure 1: (a) Picture of LiDAR LR08; (b) Picture of LiDAR Z300; (c) LiDAR locations at Taipei Tech Campus

3. CFD SETUP

The CFD analysis was conducted to reproduce the atmospheric boundary layer flow over the Taipei Tech campus and its surrounding urban environment under an easterly wind condition, consistent with on-site observations and wind-tunnel characterisation of the approach flow. Two representative scenarios were considered. In Case 1, the computational domain covered the campus and its immediate surroundings within an approximate radius of 200 m. In Case 2, the domain was extended eastward to include about 5.1 km of upstream urban fetch, allowing the influence of distant building clusters on the campus wind environment to be explicitly resolved. The numerical model was constructed from detailed three-dimensional building data and subsequently simplified and repaired to obtain a watertight geometry suitable for meshing, while retaining the essential features of the urban canopy. The horizontal extent of the domain was chosen such that the upstream, downstream, and lateral boundaries were all located 500 m away from the outermost buildings, thereby minimising blockage and artificial confinement of the flow. Vertically, the domain height was set to 1,000 m for Case 1 and 600 m for Case 2, providing sufficient depth for the development of an equilibrium atmospheric boundary layer above the urban roughness sublayer. A non-uniform, unstructured mesh was generated using a graded distribution: relatively fine cells were placed around campus buildings and near the ground and coarsened gradually towards the outer boundaries according to a geometric stretching ratio. The global maximum cell size was limited to approximately 50 m. In comparison, boundary layer-type prism meshes with a minimum height of about 0.05 m were wrapped around building façades and the ground surface to better capture near-wall velocity gradients. The resulting grids contained about 29 million cells for Case 1 and 60 million cells for Case 2.

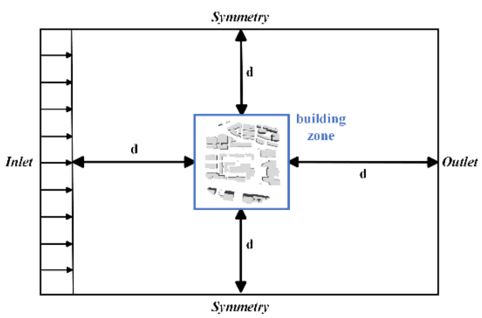
At the inlet, a horizontally homogeneous atmospheric boundary layer profile was prescribed. The mean wind direction was aligned with the dominant easterly flow identified from LiDAR field measurements at the campus, and the vertical profile of mean wind speed followed a logarithmic law fitted to a "terrain B" boundary layer realised in the multiple-fan wind tunnel, ensuring consistency between numerical, field, and experimental representations of the inflow. A mean-pressure outlet condition was imposed at the downstream boundary, while symmetry conditions were applied to the lateral and top boundaries. All building surfaces and the ground were modelled as no-slip walls. The computations were carried out with OpenFOAM, solving the incompressible Reynolds-averaged Navier–Stokes equations in combination with the Realizable k-ε turbulence model. This configuration provides a practical yet sufficiently detailed framework for assessing the campus-scale wind speed profiles and flow patterns relevant to the CWE investigation.

(a) Campus Fetch

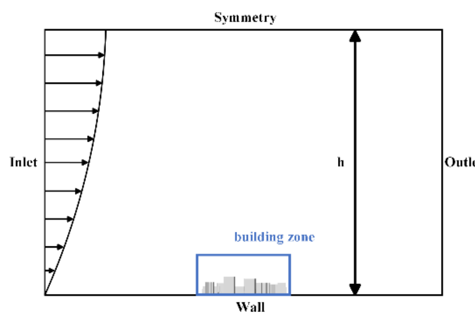


(b) Case 1: Campus (left) Case 2: Campus+Fetch (right)

Figure 2: Simulated campus and fetch path



(a) Top view of the computational domain

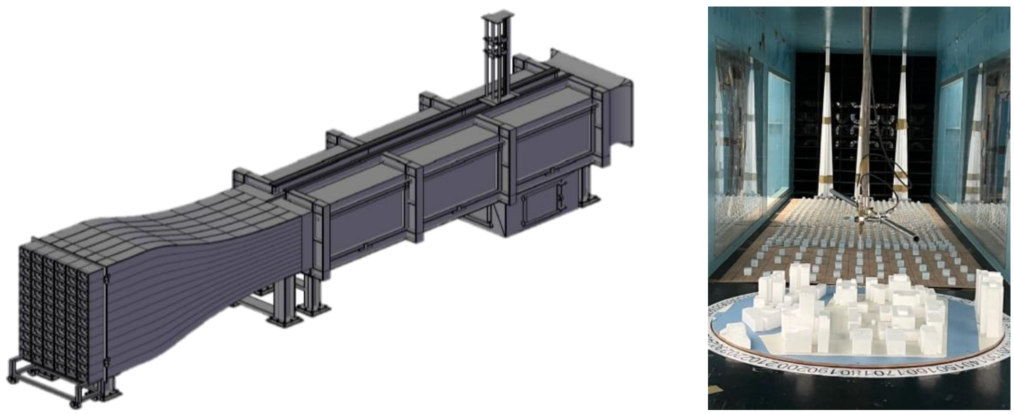


(b) Side view of the computational domain

Figure 3: Computational fluid dynamics simulation diagrams for computational domain

4. WIND TUNNEL TEST BASED ON MULTIPLE-FAN WIND TUNNEL

The wind-tunnel experiments were conducted in the multiple-fan wind tunnel at Tamkang University, which is a mid–low-speed facility equipped with 72 independently driven fans arranged in a 6 × 12 array at the inlet of a 5.57 m long test section with a 1.32 m × 1.32 m cross-section and an operating speed range of approximately 1–15 m/s. Each fan is controlled by an active feedback system that allows the target mean velocity profile at the inlet to be prescribed with high flexibility. For the present study, the Taipei Tech campus and its surrounding urban fabric were installed in the test section. The model included the main campus and an upstream urban fetch of about 1.7 km in the easterly wind direction, so that the cumulative roughness effects of the surrounding building clusters could be represented before the flow reaches the campus core. By assigning appropriate rotational speeds to the fan array, an urban boundary layer consistent with the easterly inflow observed by on-site LiDAR measurements was generated at the upstream end of the campus model. Within this configuration, vertical wind speed profiles were measured above two key rooftop locations, namely the Civil Engineering Building and the Integrated Science Building, at several heights spanning the depth of the campus boundary layer. Time histories recorded at each height were post-processed to obtain the mean velocity, turbulence intensity, and spectral characteristics, which were then compared with the corresponding LiDAR profiles. These measurements provide a controlled experimental dataset for assessing the multiple-fan wind tunnel's ability to reproduce site-specific inflow conditions and for validating numerical simulations of the campus wind environment.

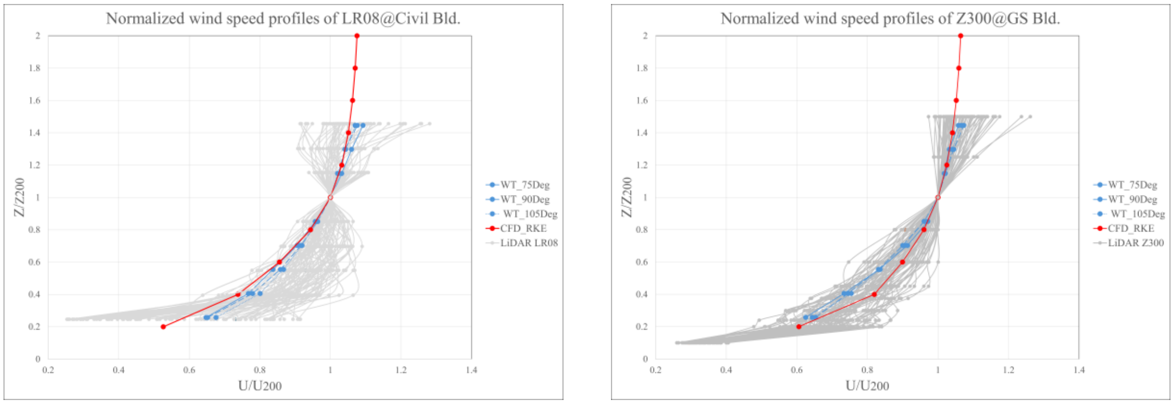


(a) Multiple-fan wind tunnel at TKU (b) Photo of experimental setup

Figure 4: Experimental setting of wind speed profile measurement in this study

5. PRELIMINARY RESULTS

Preliminary comparisons among wind-tunnel, CFD, and lidar results show encouraging consistency in the campus wind environment. Under the easterly inflow condition, three wind-tunnel configurations were tested at incident angles of 75°, 90°, and 105°. The resulting vertical profiles measured above the Civil Engineering Building and the Integrated Science Building are very similar among these three angles. They also agree closely with the CFD predictions. This indicates that the upstream simulation of the urban boundary layer using terrain category B roughness elements and turbulence-generating devices in the multiple-fan wind tunnel can reproduce the target inflow with satisfactory accuracy. In contrast, the lidar-derived wind-speed profiles exhibit substantial scatter due to atmospheric variability and data-quality fluctuations; however, most instantaneous profiles tend to correspond to relatively low power-law exponents, falling between typical open-country and small-town exposure conditions. When the two lidars are compared, the Z300 system appears to provide somewhat more stable profiles than the LR08 at the campus scale. Significantly, the CFD-predicted profiles generally lie close to the median of the lidar ensemble, suggesting that the numerical model captures a representative mean state of the urban boundary layer rather than a single realization. Overall, these preliminary results demonstrate a reasonable level of consistency among field measurements, wind-tunnel experiments, and CFD simulations, and they support the use of the combined approach for subsequent analysis of the Taipei Tech campus wind environment.



(a) LR08@Civil Bld. (b) Z300@GS Bld.

Figure 5: Vertical profiles of 10-minute mean wind speeds at Taipei Tech campus

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