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CFD prediction of ABL profiles for wind tunnel applications

Ulf Winkelmann[1], Chiron Ajit Kumar[1], Agnieszka Kocoń[2], Aleksander Pistol[3]

[1]Ruhr University Bochum, Bochum, Germany, ulf.winkelmann@rub.de
[2]Czestochowa University of Technology, Częstochowa, Poland
[3]Manchester Metropolitan University, Manchester, UK

SUMMARY
This study presents RANS simulations conducted as part of the ERIES-WhICH ROUGH project to support wind tunnel experiments undertaken at Eindhoven University of Technology (TU/e). Using OpenFOAM with the k-ω SST turbulence model, three cases are investigated: validation against measured equilibrium boundary layer profiles generated with turbulent vortex generators and L-shaped roughness elements; prediction of terrain category transition profiles using prescribed inlet conditions of equilibrium profiles and roughness elements; and equilibrium profile validation using L-shaped roughness elements only. Results demonstrate good agreement in mean velocity profiles, though near ground turbulence intensity is overpredicted due to the inherent limitations of steady-state RANS. A key challenge is the geometric disparity between the 27 m test section and the 1.5 mm roughness elements, demanding significant mesh refinement. Despite this, the approach is deemed sufficiently accurate to explore flow configurations beyond those physically tested in the wind tunnel.

Keywords: CFD, ABL profiles, validation, terrain roughness, digital twin

1. INTRODUCTION

Wind loading due to atmospheric boundary layers (ABL) under equilibrium conditions is codified in EN 1991-1-4 (Eurocode, 2010) for various surface roughness categories. However, the effect of upstream surface roughness on changes and the resulting transition between boundary layer profiles is not yet fully implemented in current models. A central question therefore remains: Can transition wind profiles be simplified to improve their ease of use in wind loading procedures?

The ERIES-WhICH ROUGH project's central objective is to quantify how changes in upwind surface roughness and the resulting shifts in boundary layer structure from equilibrium to transition profiles can be modelled in wind tunnel experiments, how they alter the aerodynamic loading on tall buildings and ultimately how a codified design framework can be developed (Rizzo et al., 2026). The numerical analyses presented here constitute exemplary partial results from the project, addressing two primary objectives:

1. Preparatory simulations conducted prior to the physical experiments in the TU/e wind tunnel, aimed at optimizing subsequent experiments for the generation of transition profiles.
    a) Numerical validation of the computational approach against measured time-averaged equilibrium velo2city profile and turbulent intensity profile for terrain category II (according to the EN 1991-1-4 (Eurocode, 2010)), employing spires in conjunction with L-shaped surface roughness elements Case 1a).
    b) Transition profile prediction through the implementation of prescribed inlet velocity profiles corresponding to terrain category II, supplemented by variations of L-shaped

roughness elements within the numerical domain, to simulate boundary layer transitions from terrain category II→III (Case 1b).

2. Equilibrium profile validation using exclusively L-shaped ground roughness elements to assess the standalone roughness-induced boundary layer development as presented in (Rizzo et al., 2026)(Case 2).

A key computational challenge arises from the geometric disparity inherent to the discretised wind tunnel model: the test section spans 27 × 2 × 3 m, while the L-shaped surface roughness elements have a width of merely 1.5 mm. This problem demands careful consideration of the trade-off between spatial resolution and computational cost, requiring a targeted strategy to ensure sufficient numerical accuracy in the near-wall region without prohibitive resource expenditure.

2. METHODS

Steady-state Reynolds-Averaged Navier–Stokes (RANS) simulations are performed following state-of-the-art best practice guidelines using OpenFOAM v. 2212. The turbulent air flow is modeled as incompressible using the k-ω SST turbulence model (Menter et al., 2003; Rizzo et al., 2026)). The governing equations are discretized through Finite Volume Method (FVM) and convective terms are discretized using second-order upwind schemes. A segregated approach is employed to solve coupled equations using the SIMPLEC algorithm.

At the inlet of the numerical domain, a fully developed atmospheric boundary layer (ABL) velocity profile corresponding to terrain category II is imposed for a Case 1b. Otherwise, a uniform velocity profile is defined where the ABL develops in the domain (Case 1a, 2). The numerical domain dimensions are set to match the cross-sectional dimensions of the TU/e wind tunnel for Case 1a and Case 1b. For Case 2, periodic boundary conditions are applied to the sides of the domain, helping to limit the required computational power.

3. RESULTS

3.1 Validation of equilibrium profiles using turbulent vortex generators (Case 1a)

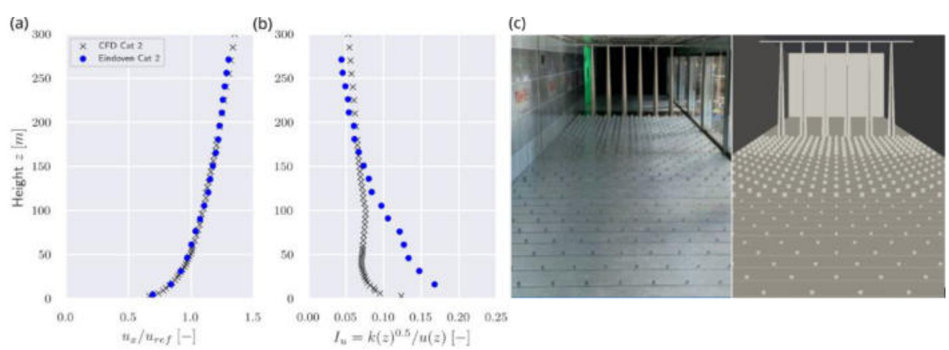
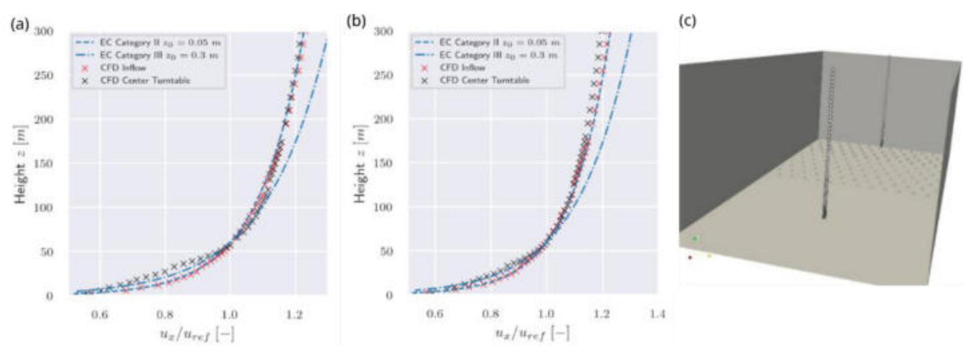


Figure 1. Normalized time-averaged velocity profile in (a). Here, u_x is the velocity component in the main flow direction. Profile of turbulence intensity I_u in (b). Blue dots show experimental validation data from the TU/e wind tunnel and black crosses show numerical results. (c) shows a photo of the wind tunnel and the numerical domain modeling the whole wind tunnel including all vortex generators and L-shaped roughness elements.

Results of normalized mean velocity and turbulence intensity profiles are shown in **Figure 1** (a, b) for full-scale measures assuming a geometric scale of 1:300 (This scale was assumed for the cases 1a and 1b only). **Figure 1** (c) depicts a photo of the wind tunnel setup and its digital twin in the CFD simulations.

3.2 Prediction of transition profiles (Case 1b)

Figure 2**Figure 2 presents the numerically predicted boundary layer transition profiles from terrain category II to III for two roughness element configurations. In configuration (a), the deployment of 10 uniform strips of 6×6 cm L-shaped elements induces excessive near-ground flow deceleration, indicating that the applied roughness density and element size overshoot the target profile for terrain category III. A mixed configuration was therefore examined, combining 4 strips of 6×6 cm elements with 6 strips of 4×4 cm elements. As shown in (b), this arrangement yields significantly improved agreement with the target category III velocity**



profile in the near-ground region. The corresponding measurement locations and numerical domain geometry are illustrated in
Figure 2 (c).

Figure 2. Normalized velocity profiles for transition profile prediction in (a, b). u_x is the velocity component in the main flow direction. Blue lines show velocity profiles according to EN 1991-1-4 for terrain category II and terrain category III; red crosses are CFD results at the inlet, black crosses are CFD results behind the L-shaped elements. (c) shows the measurement locations of the profiles.

3.3 Validation of equilibrium profiles without turbulent vortex generators (Case 2)

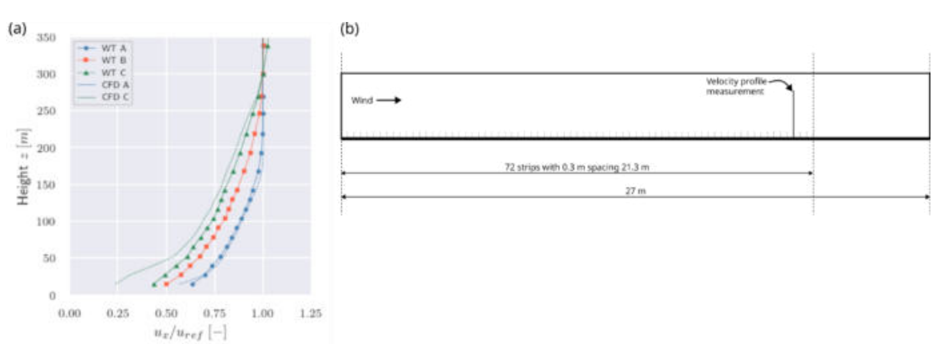


Figure 3. (a) Normalized velocity profiles for three equilibrium profiles using L-shape roughness elements only.

u_x is the velocity component in the main flow direction. A: using 2x2 cm, B using 4x4 cm, and C using 6x6 cm roughness elements only cf. (Rizzo et al., 2026). (b) sketch of the domain setup.

Figure 3 (a) shows the predicted equilibrium profiles using L-shaped roughness elements only assuming a geometrical scale of 1/492 and a uniform velocity profile at the inlet in accordance with the wind tunnel experiments (Rizzo et al., 2026). For each case, 72 strips of roughness elements are placed on the ground, see **Figure** 3 (b). Validation of CFD simulations against wind tunnel data demonstrates particularly good agreement for the 2×2 cm L-shaped roughness configuration. With increasing ground roughness (cases B and C), both datasets reveal a more pronounced near-surface velocity deceleration.

4. DISCUSSION AND CONCLUSIONS

Steady-state RANS simulations with the k-ω SST turbulence model prove suitable for predicting the mean ABL flow field, showing mostly good agreement with wind tunnel data. As inherent to the steady-state framework, turbulence intensity cannot be reliably predicted. LES would offer superior fidelity (Thordal et al., 2020); Kostadinović Vranešević et al., 2022) but is computationally expensive due to the mesh resolution (Case 2-CFD C alone required over 175 million cells) and CFL-constrained time steps imposed by the 1.5 mm roughness elements. Nevertheless, employing periodic boundary conditions on the sides limiting the wind tunnel width to 0.22 m (instead of the original 3 m) is deemed to be sufficiently accurate to investigate further configurations while saving substantial computational costs.

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