WIND TUNNEL VALIDATION OF CFD VELOCITY FIELDS IN DIFFERENT TURBULENT CONDITIONS TO ASSESS MEASUREMENT BIASES OF ATMOSPHERIC PRECIPITATION GAUGES

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In situ atmospheric precipitation measurements are the essential source of information about the precipitation process, its spatiotemporal variability, and observed frequency. Two main classes of in situ measurement instruments can be identified: catching gauges (CGs), collecting precipitation into a container before the accumulated volume of water is measured over a given period using various principles, and non-catching gauges (NCGs), requiring no container to collect precipitation. CGs are characterized by a radially-symmetric shape while NCGs are more complex geometries dictated by the measurement principle (mainly optical and impact) adopted to derive precipitation measurements. All instruments are subject to measurement biases due to environmental and instrumental sources [1]. In this work the exposure effect induced by wind [2] is numerically addressed by performing CFD simulations to calculate the airflow velocity fields around an aerodynamic CG and an optical NCG by considering different turbulent conditions both in terms of turbulence developed by the gauge itself when impacted by wind and free-stream turbulence. Indeed, any gauge immersed in a wind field acts as a bluff-body and generates an aerodynamic response that depends on its geometry. Airflow deformations occur around the gauge body, with significant acceleration and vertical velocity components arising especially just above its measurement section. These airflow features have the potential to deviate the trajectories of the approaching hydrometeors, generally inducing some underestimation of the measured precipitation than in the absence of wind. The hydrometeor-airflow interaction can be investigated by implementing a Lagrangian particle tracking model [3] as discussed in a companion abstract [4].

In this work URANS and LES were performed and two different free-stream turbulent conditions were set. CFD velocity fields were validated in the wind tunnel (WT) facility available at the Department of Civil, Chemical and Environmental Engineering (DICCA) of the University of Genova. The WT has a working section with a total length of 8.8 m and a cross area of 1.7×1.35 m^2 (width × height). Measurements were taken using a multi-hole pressure probe, called "Cobra", attached to a traversing arm with three-degrees of freedom. By measuring the local pressure, the Cobra probe provides the three velocity components of the flow. Measurement were taken at a frequency of 1000 Hz for a duration of 30 s in chosen positions above the measurement section of each investigated gauges. Various wind speeds (U_{ref}) from 2 to 20 m s^{-1} were simulated and some of them were reproduced in the WT, while different wind directions (α) were also tested in the case of NCG by rotating the instrument with respect to the incoming wind.

The first comparison here presented is extrapolated by the work of Cauteruccio et al. [5], where URANS SST k-ω simulations were performed and compared with WT measurements under two free-stream turbulence conditions: 1) smooth flow characterized by a turbulence intensity $I_{turb}\sim$ 0.5% and 2) turbulent flow characterized by $I_{turb} \sim$ 10% produced through a square grid positioned upstream of the gauge. An inverted conical shaped gauge (see Figure 1 left-hand panel) with a small size (collector diameter D equal to 0.13 m and height equal to 0.192 m) was chosen because the aerodynamic shape reduces the development of turbulence and allows to better single out the role of free-stream turbulence on the airflow features above the gauge collector.

A good agreement between WT measurements and numerical results was observed for both the uniform (central panel of Figure 1) and turbulent (right-hand panel of Figure 1) free-stream conditions with differences on the order of 0.010 U_z/U_{ref} and 0.030 U_z/U_{ref} at a few measurement elevations along the vertical profile in the upwind edge of the gauge. These differences are justified since the velocity values in such cases approach the minimum threshold velocity that the Cobra probe is able to measure (about 2 m s^{-1} to get reliable values). Also, the Cobra probe is unsuited to measure reverse flow components.

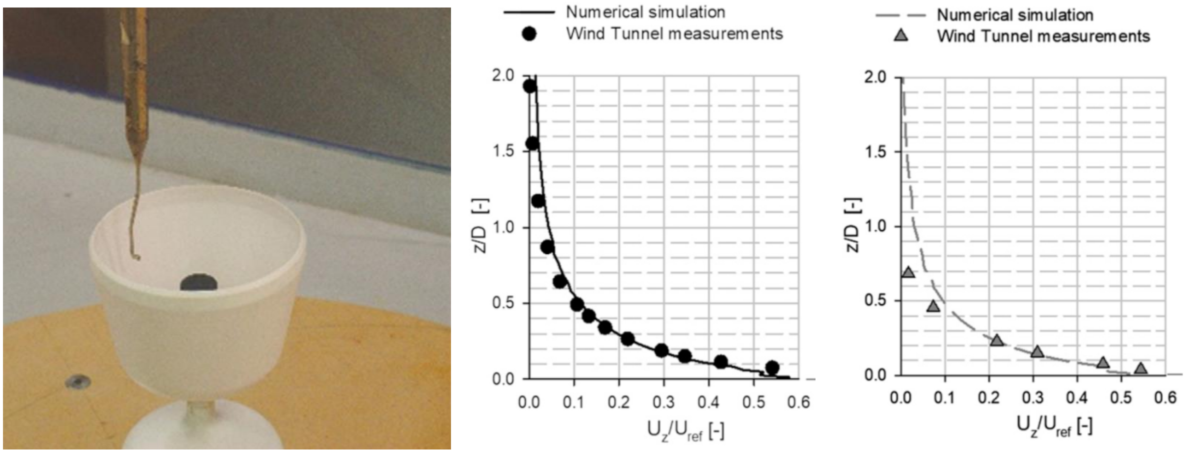

Figure 1: Aerodynamic CG and the Cobra probe installed in the DICCA WT (left-hand panel), WT measurements (markers) and simulated profiles (lines) of the normalized vertical velocity U_z/U_{ref} at the upwind edge of the collector along the non-dimensional vertical direction z/D for the uniform free-stream conditions (U_{ref} = 18 m s^{-1}) in the central panel and for the turbulent free-stream condition (U_{ref} = 10 m s^{-1}) in the right-hand panel. Source [5]

Results revealed that contrary to the turbulence intensity, the normalized vertical velocity components (U_z/U_{ref}) are less accentuated for the turbulent free-stream configuration than in a uniform free-stream, with relative percentage differences of about 18% and 46% on the upwind and downwind edges of the gauge collector, respectively. The analysis was limited to the effect of turbulence on the airflow deformation around and above the gauge, while the impact of free-stream turbulence on the hydrometeors trajectories was addressed in [6]. Nevertheless, the obtained results confirm that neglecting the free-stream turbulence intensity in the numerical simulation of the airflow field leads to a biased assessment of the wind-induced undercatch of catching type precipitation gauges.

The second case study reports numerical simulation results and the WT validation for an optical NCG (the Thies LPM) characterized by a non-radially symmetric shape (see left-hand panel of Figure 2). In this case only the uniform free-stream condition was simulated and a comparison between LES and URANS simulation results was performed. URANS SST k-ω simulations were run with a pseudo-transient approach based on a local time stepping (LTS) numerical scheme to reduce the computational burden, avoiding downgrading to a RANS approach. In that case, wind speed values equal to 2, 5, 10, 15, and 20 m s^{-1} and wind directions from $\alpha = 0°$ to $\alpha = 180°$ with increments of 22.5° were simulated. The computational domain, 4m x 2.4 m x 2 m in size, was discretized using high resolution meshes with over 4M cells.

A limited number of wind speeds (5 and 10 m s^{-1}) and directions (0° and 90°) were also investigated using the LES approach with the objective to quantify the approximation introduced by URANS simulations on the assessment of the measurement bias. The WALE (Wall-Adapting Local Eddy-viscosity) turbulence model was adopted for running the simulations, considering the same computational domain, discretized using a much higher resolution mesh (from 20M to 25M cells). To improve convergence, LES were initialized by running precursor URANS simulations over the finer meshes. Refinements were furthermore evaluated by computing the ratio between the turbulence integral length scale and the cell size, shown to be above 10 for the entire domain, except very close to the gauge body.
Figure 2 (centre and right-hand panels) shows the results of the LES for two different wind directions, where a significant generation of turbulence near the instrument body is evident. In the case of α = 0°, turbulent structures in the wake of the gauge receiving head (on the left in the central and right-hand panels) insist on the instrument sensing area, while for α = 90° the wake is directed away from the sensing area, that remains for the most part undisturbed.

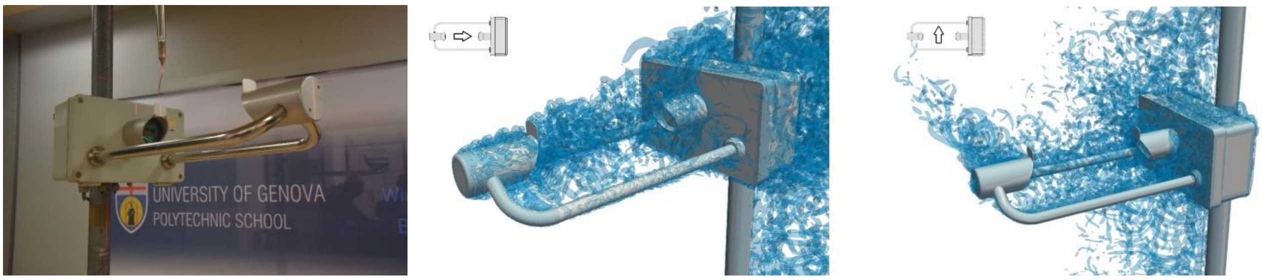

Figure 2: Image of the Thies LPM optical NCG installed in the DICCA wind tunnel (left-hand panel). Visualization of the turbulent structures around the gauge body using the Q-criterion on the LES results for a wind direction of α = 0° (central panel) and α = 90° (right-hand panel), at a wind speed of 5 m s^{-1}

Numerical simulations were validated by means of flow measurements taken in the DICCA WT, where the gauge was installed on a rotating platform, allowing different wind directions to be reproduced.

Figure 3 shows examples of the comparison between WT measurements and CFD results. The URANS approach (Figure 3, left-hand panel) shows very good agreement even close to the gauge where high turbulence is present and provides almost perfect agreement in more favourable configurations. In total, 661 WT measurements were used for validation (considering different wind speeds and directions) and only a small fraction (6.65%) falls outside of the probe tolerance.

In Figure 3, central panel, the same comparison is shown for the LES results. For this specific profile, the agreement with WT measurements is lower, possibly due to an insufficient mesh refinement close to the very thin shield mounted over the instrument receiving head. Other investigated profiles and configurations (not shown here for conciseness) are however in almost perfect agreement with both WT measurements and URANS results.

The LES approach better captures the flow pattern inside the recirculation zone (Figure 3, right-hand panel) where the URANS model is not in a similarly good agreement.

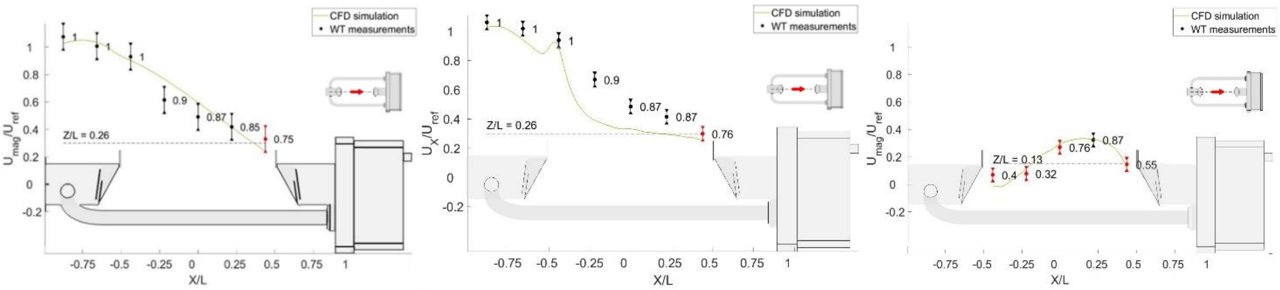

Figure 3: Comparison of the simulated flow velocity profile against WT measurements for the configuration at α = 0° and U_{ref} = 5 m s^{-1} for the URANS approach (left-hand panel) and the LES approach (central and right-hand panels)

In conclusion, the URANS SST k-ω model with a pseudo-transient approach based on LTS is a valid option for resolving the flow near the complex shape typical of NCGs, especially far from the recirculation zones that are instead better resolved by the LES approach. The limited computational burden of such approach in comparison to the LES furthermore allowed us to investigate a large number of wind speeds and directions, that becomes a necessity in the case of NCGs because of their non-radially symmetric geometry.

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