Thermo-fluid dynamic simulations of the Hotplate precipitation gauge and wind tunnel experiments

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HIGHLIGHTS

- *Wind is the primary cause for precipitation undercatch in rain gauge measurements.*
- *The wind effect on a thermodynamic precipitation gauge is addressed.*
- *Computational Fluid Dynamics (CFD) simulations are used to assess streamlines around the gauge.*
- *The heat effect on the airflow is estimated using conservation of energy.*
- *Validation of the CFD results is provided by comparison with wind tunnel measurements.*

Abstract:

The present study addresses the aerodynamic response of the recently developed "Hotplate" precipitation gauge when exposed to the wind. The Hotplate gauge employs two heated plates to provide a reliable method of precipitation measurement. The measuring principle is based on an algorithm to associate the latent heat needed to evaporate the snow, or the rain, and the precipitation rate. The presence of the instrument body immersed in a wind field is expected to induce significant deformations of the airflow pattern near the gauge, with an impact on the associated catching efficiency. Indeed, the fall trajectories of the hydrometeors when approaching the gauge can be deviated away from the collecting plate resulting, in general, in some underestimation of the precipitation rate.

This work is based on Computational Fluid Dynamics (CFD) simulation of the airflow field around the gauge for different wind speeds, to identify areas where the wind-induced updraft, local acceleration and turbulence are significant. The performed CFD airflow simulations use the URANS SST k-ω approach, and are the initial modelling step to quantify the associated undercatch. These will be possibly coupled in future developments with particle tracking models to derive suitable correction curves for operational purposes. Due to the specific measurement principle exploited by the "Hotplate" gauge, thermo-fluid dynamic simulations are addressed as well. Dedicated tests have been performed in the wind tunnel facility available at the Department of Civil, Chemical and Environmental engineering DICCA, University of Genoa to validate simulation results.

Numerical results indicate that the presence of wind is a relevant source of systematic bias and its effect must be corrected by adopting suitable correction curves as a function of the wind velocity. An assessment of the airflow patterns developing around the gauge at various wind velocity regimes is provided in this work and wind tunnel tests allowed for a substantial validation of the numerical results.

1. Introduction

The accuracy of precipitation measurements is fundamental; precipitation intensity is the input to the study of urban drainage, to evaluate hydrogeological risks (flooding and landslides), to water resources management and the optimization of agricultural practices. Precipitation measurements are affected by errors due to instrumental and environmental sources. Wind is recognized as the main environmental factor that affects solid and liquid precipitation measurements (*Sevruk et al.,* 1991). When wind impacts the gauge body the surrounding airflow is deformed resulting in the acceleration of the flow above the collector of the instrument, which deflects the hydrometeors (liquid/solid particles) trajectories. The main factors of influence are the gauge shape, the wind speed and the type of precipitation, including the particle size distribution (PSD).

The aim of this study is to analyse the aerodynamic response of the recently developed “Hotplate” precipitation gauge.

The “Hotplate” precipitation gauge (see Figure 1 left) was developed by the National Center for Atmospheric Research (NCAR) in US. This gauge consists of two identical, heated aluminum plates: one facing upward and exposed to precipitation and the other facing downward mounted underneath the top plate. The lower plate is insulated from the top plate and is designed to serve as a reference plate that is only affected by wind and ambient temperature and not by precipitation. The precipitation rate is estimated, every minute, by calculating the power required to either melt or evaporate snow or rain on the upward-facing plate. The shape and the small size of this instrument reduce the wind effect on the precipitation collection when compared to the most common bluff shapes of traditional rain gauges (cylindrical and chimney shape). Nevertheless, experimental observations (see Figure 1 right) revealed that the wind effect is not negligible (Rasmussen et al. 2011).

This study is based on the analysis of airflow patterns in the proximity of the gauge by means of Computational Fluid Dynamic (CFD) simulations. Validation of the numerical results is obtained by comparison with wind tunnel experiments. These simulations, to be coupled in future developments with a particle tracking model to introduce the dispersed phase (solid/liquid particles), will allow to quantify the Collection Efficiency (CE) of the gauge. The overall objective is to derive suitable correction curves for operational purposes.

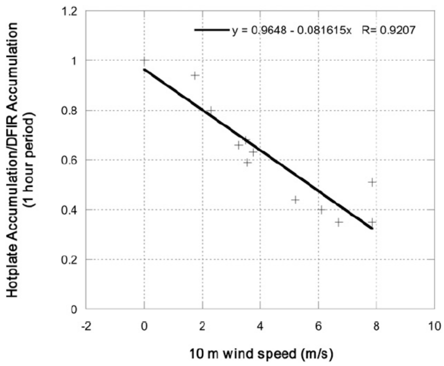

Figure 1 The Hotplate precipitation gauge (left) and the associated catch efficiency (right) calculated with respect to measurements from the DFIR (Double Fence Intercomparison Reference) using data from the 11 April 2001 snow event (Rasmussen et al.2011).

2. Methodology

The airflow patterns in the proximity of the gauge are investigated by means of CFD simulations. The open-source OpenFOAM numerical solver is used to run the Unsteady Reynolds Average Navier-Stokes (URANS) model and the conservation of energy theorem is introduced to account for the influence of the heat generated by the plates on the airflow. To solve the system of equations, the SST (Shear Stress Tensor) k- Ω closure model was adopted. Simulation results are processed to compute the velocity profiles (magnitude and components) in representative portions of the domain. Validation of the CFD results is obtained by measuring the air velocity components around the top plate of the gauge using a multi-hole pressure probe in the low turbulence wind tunnel available at DICCA (University of Genova).

2.1 The Hotplate geometry

The Hotplate precipitation gauge is suitable to measure snow and light rain. It has a diameter of 130mm and thickness of 15mm. Three concentric metallic rings, with a height of about 10, 8 and 6 mm, avoid the water leakages off the measuring plate. Using the CAD 3D software, a model of the gauge geometry was realized in stl format, suitable for use in CFD simulations.

2.2 CFD simulations

The Unsteady Reynolds Average Navier Stokes (URANS) equations with a Shear Stress Tensor (SST) k- Ω closure model have been used in this work.

The URANS equations are:

$$\frac{\partial \overline{u_i}}{\partial t} + \overline{u_j}\frac{\partial \overline{u_i}}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \bar{p}}{\partial x_i} + \upsilon\frac{\partial^2 \overline{u_i}}{\partial x_j \partial x_j} - \frac{\partial \overline{(u_j' u_i')}}{\partial x_j} \tag{1}$$

$$\frac{\partial \overline{u_i}}{\partial x_i} = 0 \tag{2}$$

where $\bar{p}$ and $\overline{u_i}$ are the average pressure [kg $m^{-1}s^{-2}$] and the average components of flow velocity [ms^{-1}], u_j' are the terms of turbulent fluctuations [ms^{-1}], ρ is fluid density [kg m^{-3}], ν is the cinematic viscosity [m^2s^{-1}]. To solve the system of equations the SST k- Ω closure model is adopted. This formulation uses two equations; the turbulent kinetic energy k [m^2s^{-2}] equation and the equation of Ω or ε. Ω is the specific turbulent dissipation [s^{-1}] and ε the dissipation rate [m^2s^{-3}]. The SST k– Ω model switches to a common k– ε behaviour in the free stream and uses the k– Ω approach near the walls (the rain gauge surfaces).

To evaluate the heat effect on the airflow the conservation of energy theorem was adopted:

$$\underbrace{\frac{d(\rho e)}{dt}}_{I} + \underbrace{\frac{d(\rho E_k)}{dt}}_{II} = \underbrace{\rho \mathbf{g} \cdot \mathbf{U}}_{III} + \underbrace{\nabla \cdot (\tau \cdot \mathbf{U}) - \nabla \cdot (\mathbf{U}p)}_{IV} + \underbrace{\rho r}_{V} - \underbrace{\nabla \cdot \mathbf{q}}_{VI} \tag{3}$$

with:

I) rate of change of internal energy (thermal energy contribution);

II) rate of change of kinetic energy (mechanic energy contribution);

III) rate of change of potential energy where g is the gravity;

IV) rate of change of strain energy where τ is the surface tension and p is the pressure;

V) the heat source for irradiation;

VI) the heat flux.

2.3 Simulation setup

The three-dimensional air velocity and pressure fields are solved with a finite volume method implemented in the OpenFOAM CDF package. The spatial domain is discretised using an unstructured hexahedral-dominated mesh. The level of details of the geometry, especially near the rings, and the presence of regions with high velocity gradients require some mesh refinements (see Figure 2a). Boxes with increasing level of detail approaching the gauge model are stretching downwind, and also upward in the case of thermo-fluid dynamic simulations (see Figure 2b,c). The quality of the mesh was verified by using the standard parameters of orthogonality, skewness, and aspect ratio.

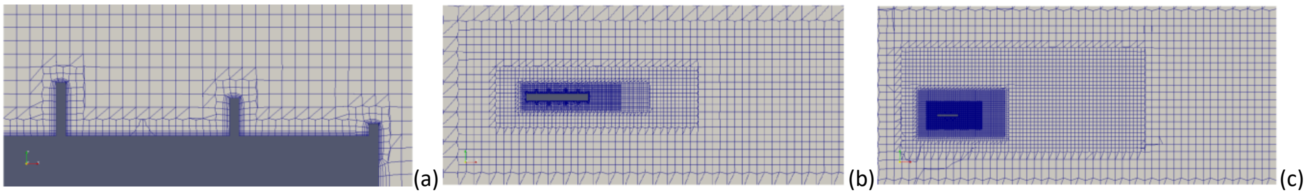

Figure 2 Refinement layers near the plate (a), mesh for fluid dynamic simulations in the vertical plane (b) and mesh for thermo-fluid dynamic simulations (c).

The three Cartesian coordinates are oriented with the x axis along the stream wise direction, the y axis along the crosswise direction and the z axis along the vertical direction. The spatial domain is composed by inlet, outlet and four lateral surfaces. In the inlet a fixed value of the undisturbed flow velocity $\mathbf{U}_w$ parallel to the x axis and a null normal gradient of pressure are set. On the outlet the flow velocity is set to a null normal gradient meanwhile the atmospheric (P_{atm}) pressure is imposed as a fixed value. Suitable boundary conditions on the inlet and outlet surfaces are imposed for k and Ω. The surfaces of the gauge body are assumed as walls with a null flow velocity, this boundary condition is necessary to impose the no slip condition. In the whole domain, initial conditions equal to $\mathbf{U}=\mathbf{U}_w$, $P=P_{atm}$ and for k and Ω are imposed.

The fluid, air, is assumed as a Newtonian incompressible fluid with kinematic viscosity $\upsilon_a= 1.2\cdot10^{-5}$ m^2s^{-1} and air density $\rho_a= 1.3$ kg m^{-3}, consistent with an air temperature $T_a= 0°C$.

Different undisturbed flow velocities are tested. For thermo-fluid dynamic simulations, the magnitude of the undisturbed flow velocity is set equal to 0.5, 5 and 10 ms^{-1}; for fluid dynamic simulations it is assumed equal to 1, 5, 10 and 16 ms^{-1}.

3. Wind tunnel experiments

Validation of the CFD results are provided by measuring in a wind tunnel the air velocity components in different fixed positions above the top plate of the gauge under the same airflow velocity conditions. The experiments were conducted in the Wind Tunnel facility available at DICCA, University of Genova. The test chamber is 8.8 m long and the cross section is 1.7 x 1.35 m^2. The chamber of the wind tunnel is a low turbulence test section.

To measure the flow velocity in different positions above the top plate of the Hotplate the *Aeroprobe Omniprobe* (with ± 150° acceptance cone) was used. This is a multi-hole pressure probe able to resolve the three components of the local velocity. The reference flow velocity inside the tunnel is detected by means of a Pitot static tube positioned in an undisturbed region.

4. Results

CFD results confirm that both the thermo-fluid dynamic and fluid dynamic cases show that the airflow above the gauge is accelerated (Figure 3) and is characterized by significant vertical velocity components (**Errore. L'origine riferimento non è stata trovata.** and 5 left).

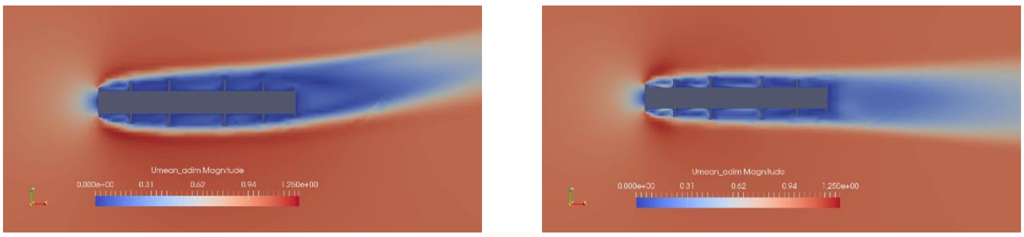

Figure 3 Average flow velocity magnitude in the vertical plane along flow direction for thermo-fluid dynamic simulation with U_w=0.5m/s (left) and U_w=10m/s (right).

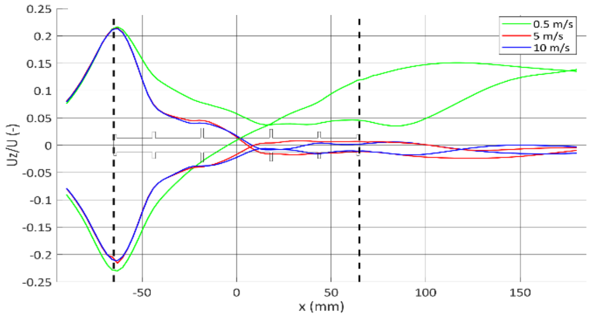

Figure 4 Longitudinal profiles of the normalized vertical velocity component for different wind speeds from thermo-fluid dynamic simulations.

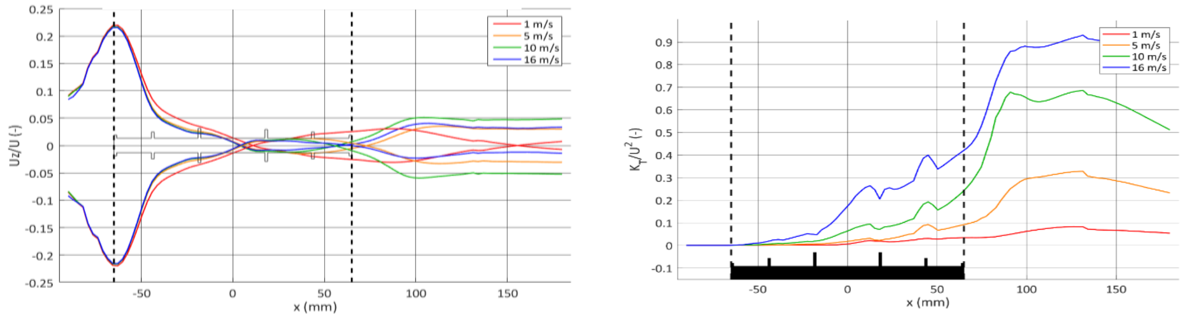

Figure 5 Longitudinal profiles of the normalized vertical velocity component for different wind speeds from fluid dynamic simulations (left) and the associated normalized turbulent kinetic energy (right)

Thermo-fluid dynamic simulations (Figure 4) reveal that the heat effect is only considerable at low wind speed, less than 1m/s, and that in the upwind half part above the plate the velocity profiles are scalable while they differ in the second half part, where turbulence is higher (Figure 5).

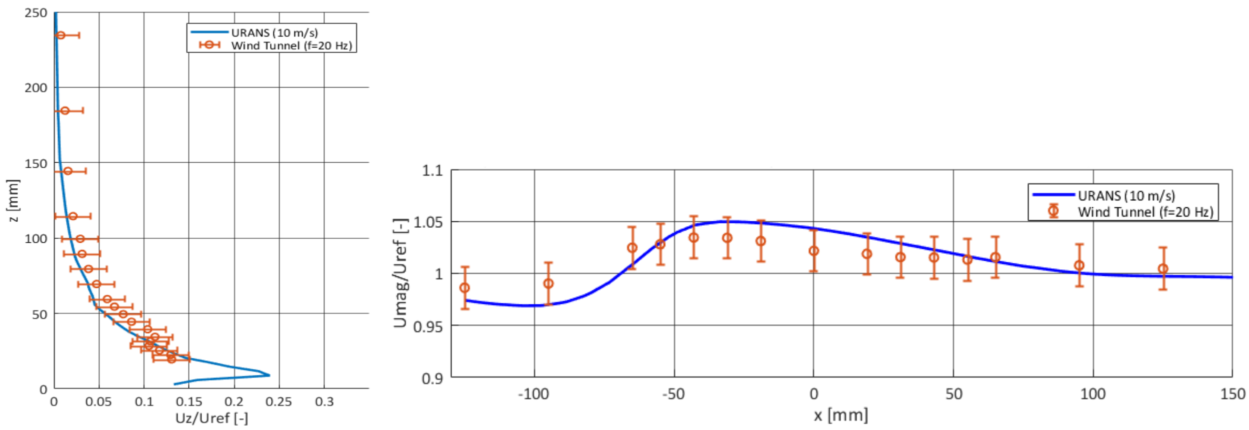

Figure 6 Comparison between URANS vertical (left) and horizontal (right) velocity profile and wind tunnel measurement above the plate.

Figure 6 reports the comparison between wind tunnel measurements (red dots) and CFD results (blue line). On the left, the normalized vertical velocity component along the vertical line located at the centre of the plate is plotted; on the right the magnitude of flow velocity along the horizontal line placed 4 cm above the plate and centred in the y direction is reported. The wind tunnel measurements are represented with the associated uncertainty.

5. Conclusions

Wind tunnel validation confirms that the CFD model adopted in this work provides, with good approximation, the airflow features in the zone of interest above the Hotplate. The thermo-fluid dynamic simulation conducted at increasing wind speed allowed to identify a threshold beyond which the heat effect can be neglected.

Future developments aim to introduce the dispersed phase (liquid, solid particles) in the CFD simulations using a particle Tracking Model to calculate the trajectories of hydrometeors and then the CE and to derive correction curves for precipitation measurements when affected by the wind for operational use. It is indeed expected that the low intensity precipitation events and especially snowfall events, characterized by large numbers of small size and light particles, can be affected by some degree of undercatch when measured using the Hotplate sensor.

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