Università di Genova | DICCA DIPARTIMENTO DI INGEGNERIA CIVILE, CHIMICA E AMBIENTALE

EGU General Assembly 2020

Evaluation of wind-induced errors for the Hotplate precipitation gauge using computational fluid dynamic simulations

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Solid precipitation has important repercussion on society

obtaining precise measurements is a priority!

Errors in precipitation gauges can be divided in two categories:

Quantification errors, that depend on the instrument measuring principle

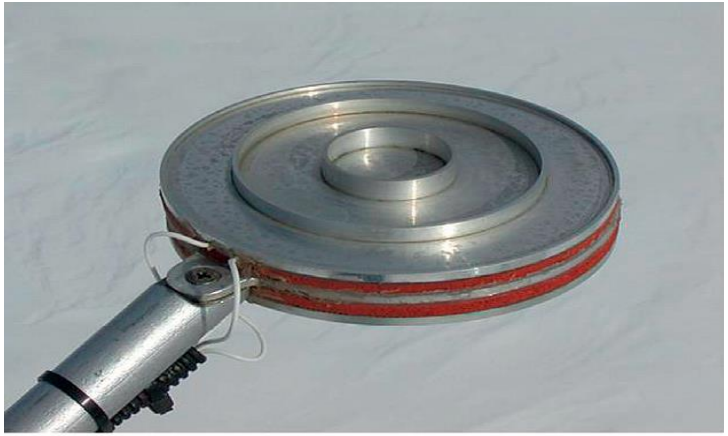
→ Laboratory calibration

Catching errors, that depend on the environmental conditions at the instrument

→ Environmental models

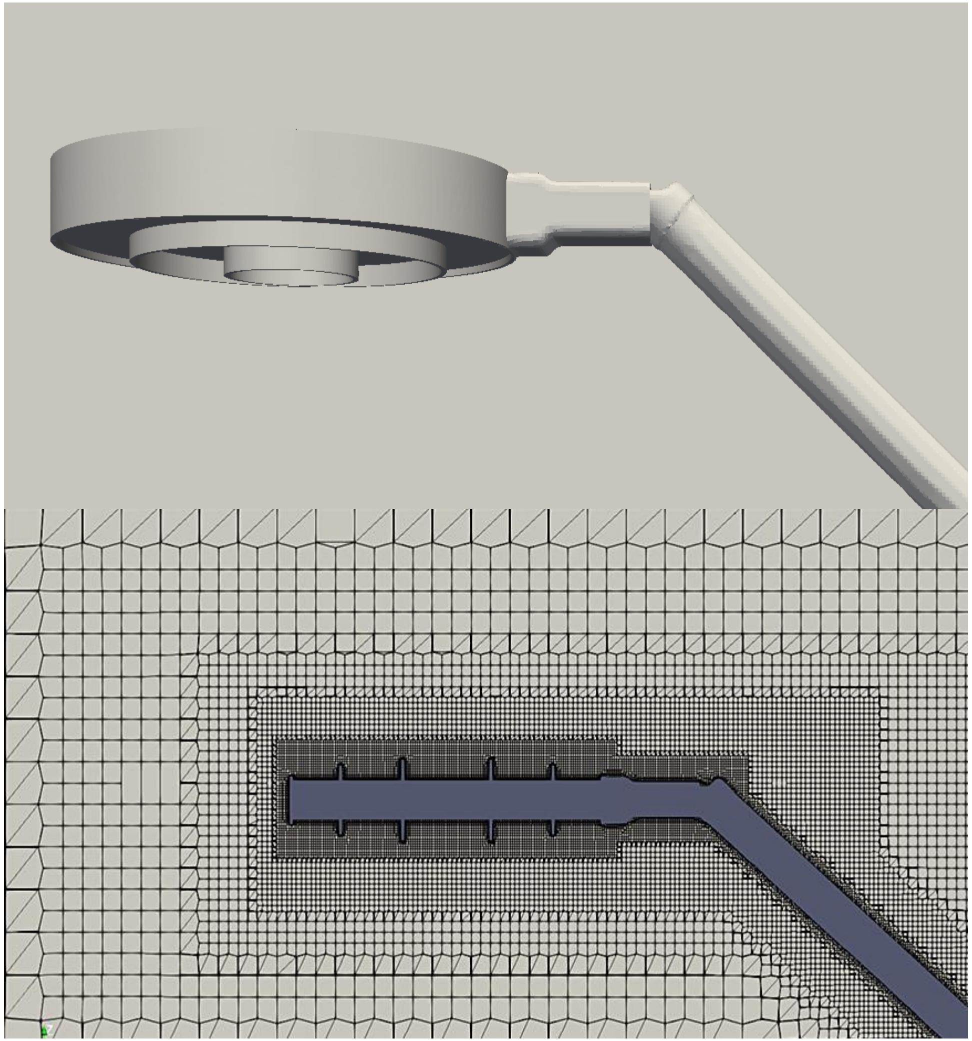
Wind is the primary source of catching errors! → Strong velocity gradients can divert the hydrometeors trajectories away from the gauge → Modelling the instrument behaviour under high wind condition is necessary!

The Hotplate precipitation gauge is an innovative instrument designed for measuring solid precipitation



Developed at the Research Applications Laboratory at the National Center for Atmospheric Research, it measures the latent heat of evaporation to estimate the precipitation rate by using two heated plates

- Requires very little maintenance
- Can operate in extreme environmental conditions
- Can provide one minute solid precipitation intensity
- Can estimate wind speed



Simulation setup

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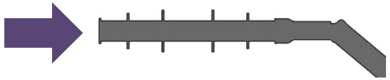
The 3D model was created in 1:1 scale and exported as STL file

The mesh is composed of 1.54M cells with progressive refinement up to 1mm cells near the instrument surface

The geometry includes the supporting arm and is enclosed in a computational volume of 1.5 x 1.0 x 0.65 m

Five different velocities were simulated: 2, 5, 10, 15 and 20 m/s

Flow direction 

Simulation results

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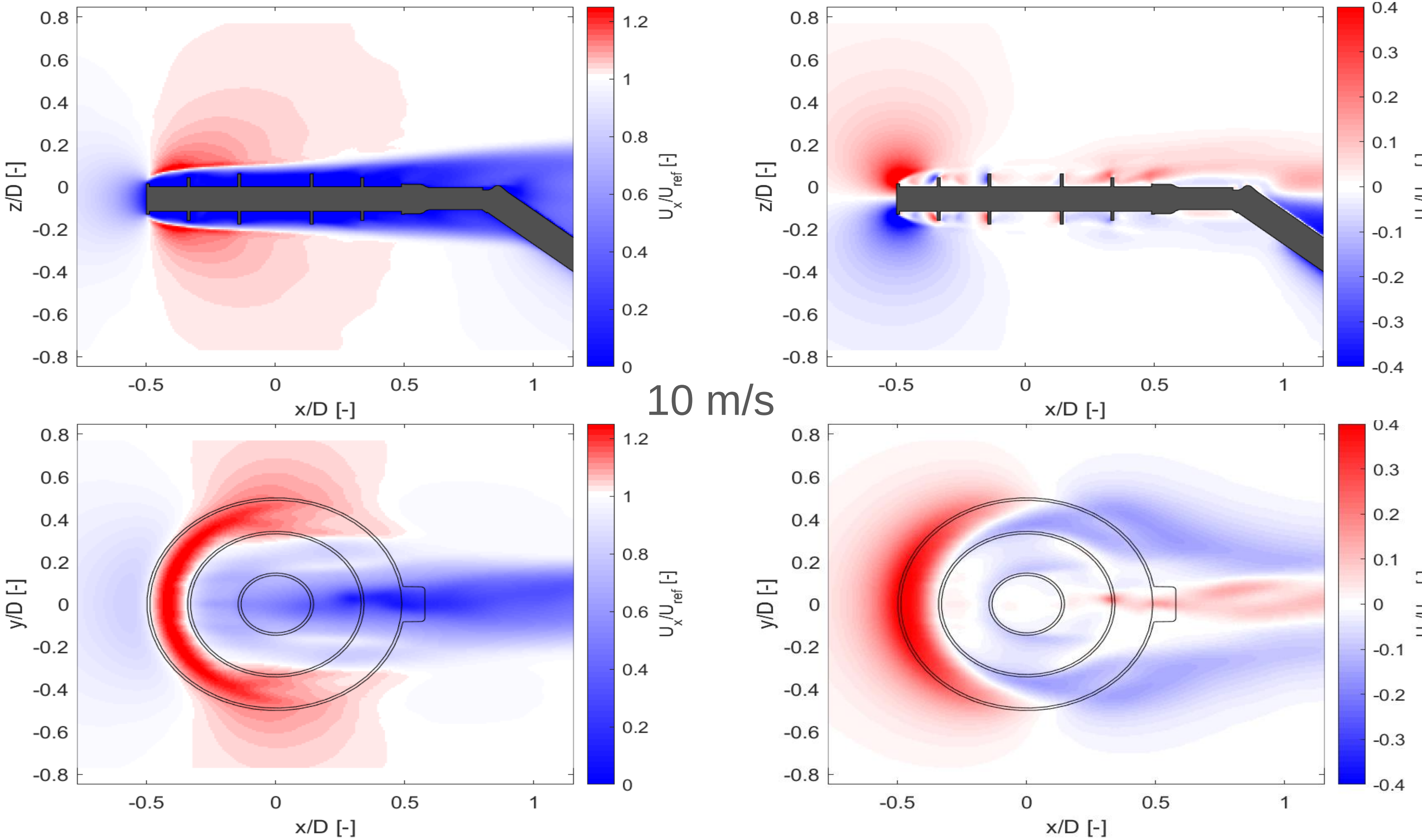
horizontal velocity



10 m/s

vertical velocity

Scalability of the solution

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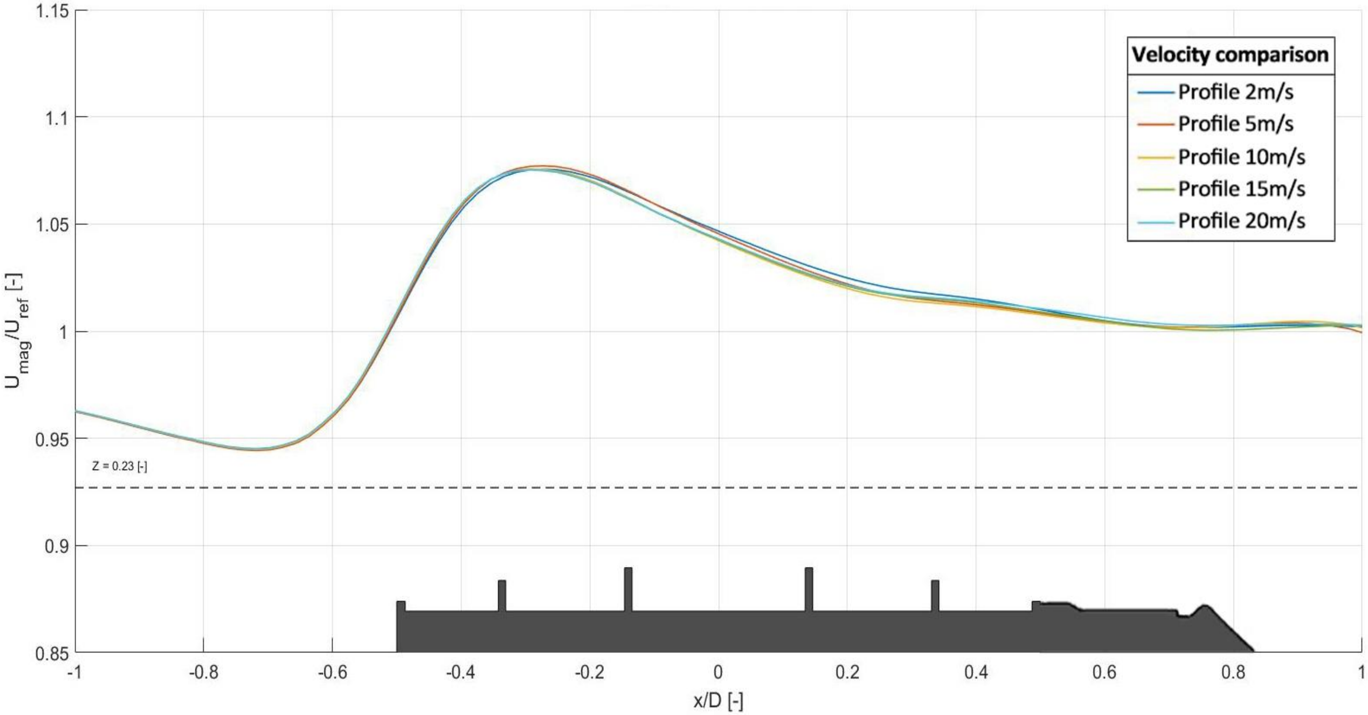
All fields shows excellent scalability, allowing to obtain intermediate velocity fields by interpolation



For further analysis the velocity fields were interpolated to obtain airflow fields for:
3.5, 7.5, 12.5 and 17.5 m/s

Wind tunnel validation

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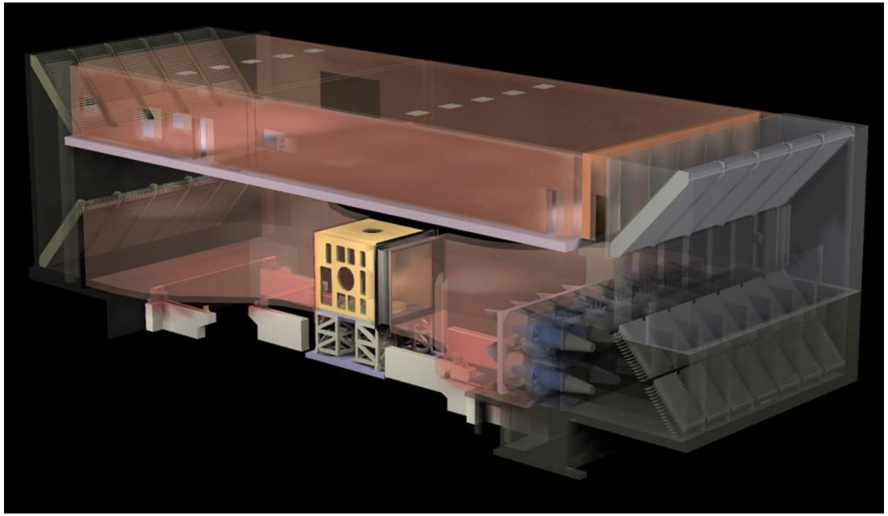
CFD introduces approximations → Wind tunnel validation is required

Politecnico di Milano wind tunnel



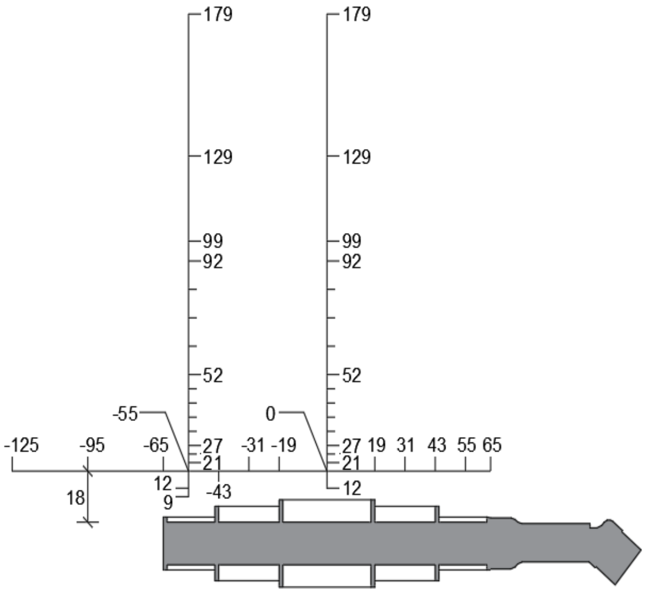
- Measurement section size: 4 x 3.84 x 6 m
- Maximum air speed 55 m/s
- Installed power 1.4 MW

University of Genoa DICCA wind tunnel

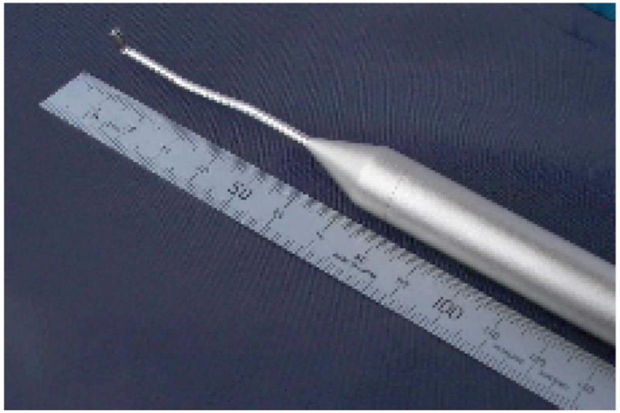
- Measurement section size: 1.7 x 1.35 x 8.8 m
- Max air speed 40 m/s
- Installed power 132 kW

Experimental setup

To validate the simulations multiple measures were taken around the instrument, using pressure probes to sample the velocity at specific positions

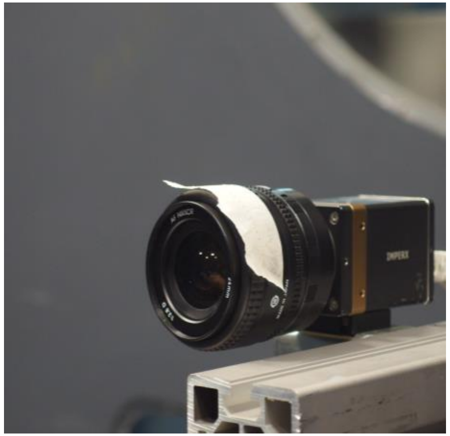


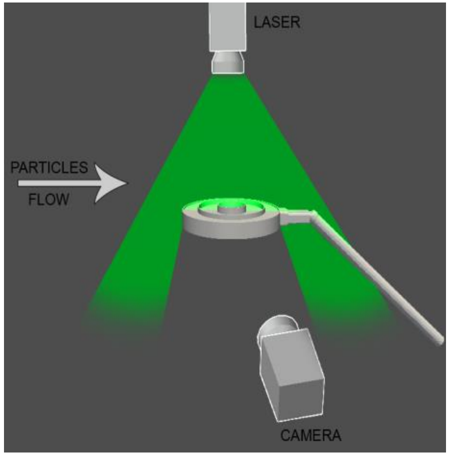
“*Cobra*” multi-hole pressure probe



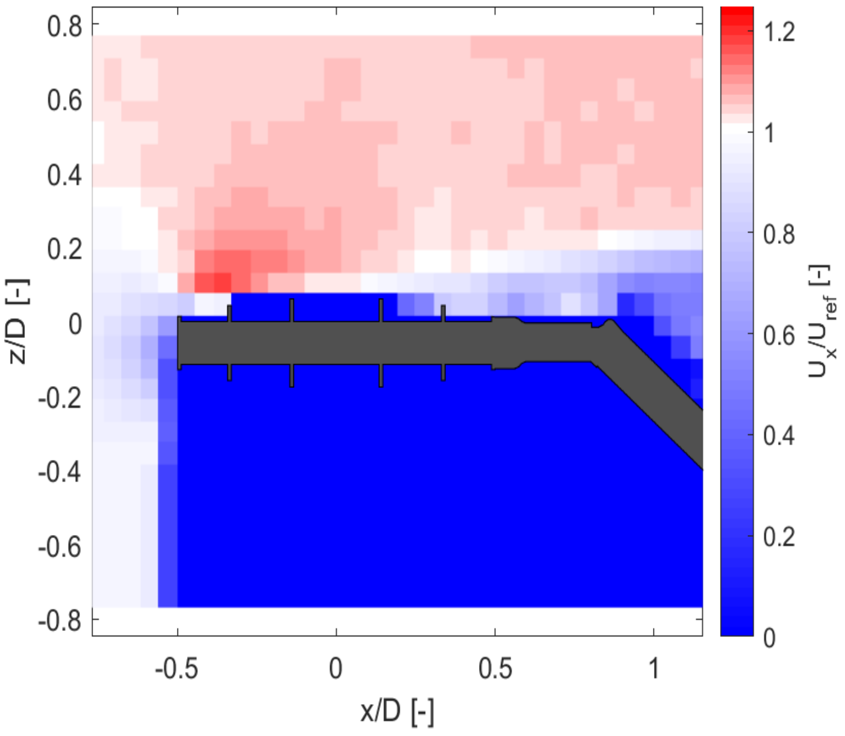
PIV results

Particles Image Velocimetry (PIV) was used in the Politecnico di Milano wind tunnel to measure the velocity field in a vertical plane

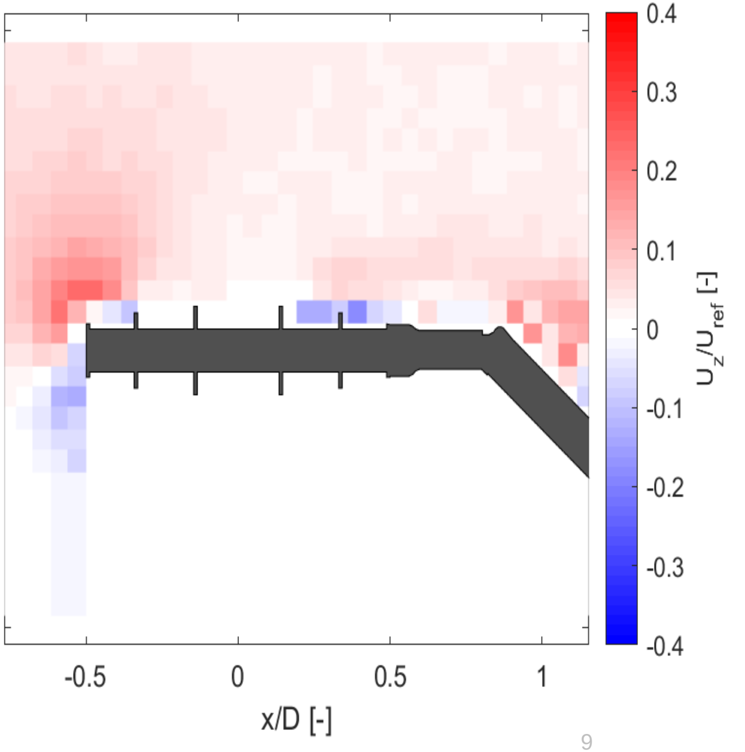


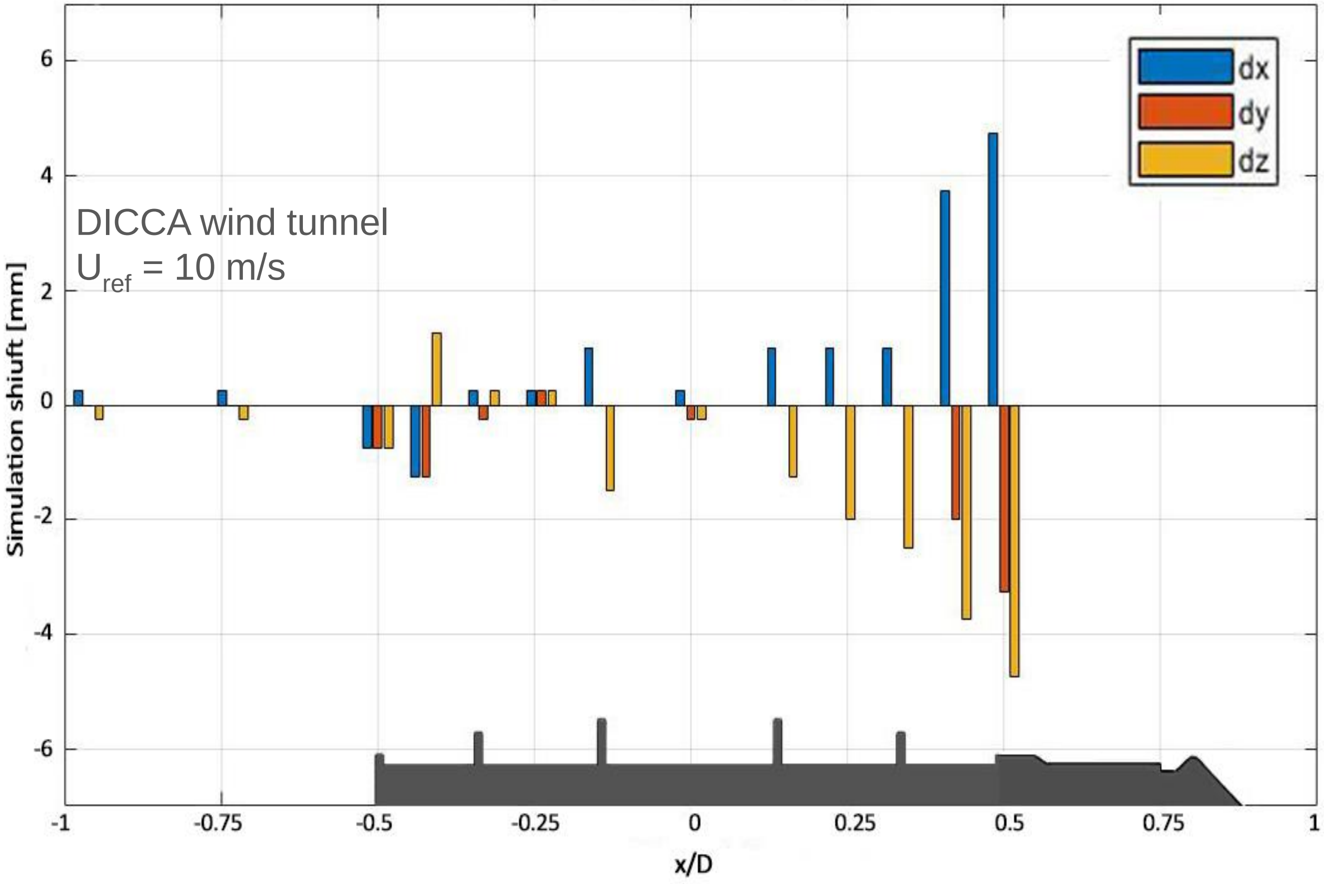


10 m/s – horizontal component



10 m/s – vertical component





Post-processing the data from the cobra probes obtained in the DICCA wind tunnel, using an algorithm that minimize the error between the simulation and probe values, a clockwise rotation of 2.5° in the vertical plane was found, caused possibly by flexing in the hotplate arm or in the connections with the supports.

DICCA wind tunnel
U_{ref} = 10 m/s

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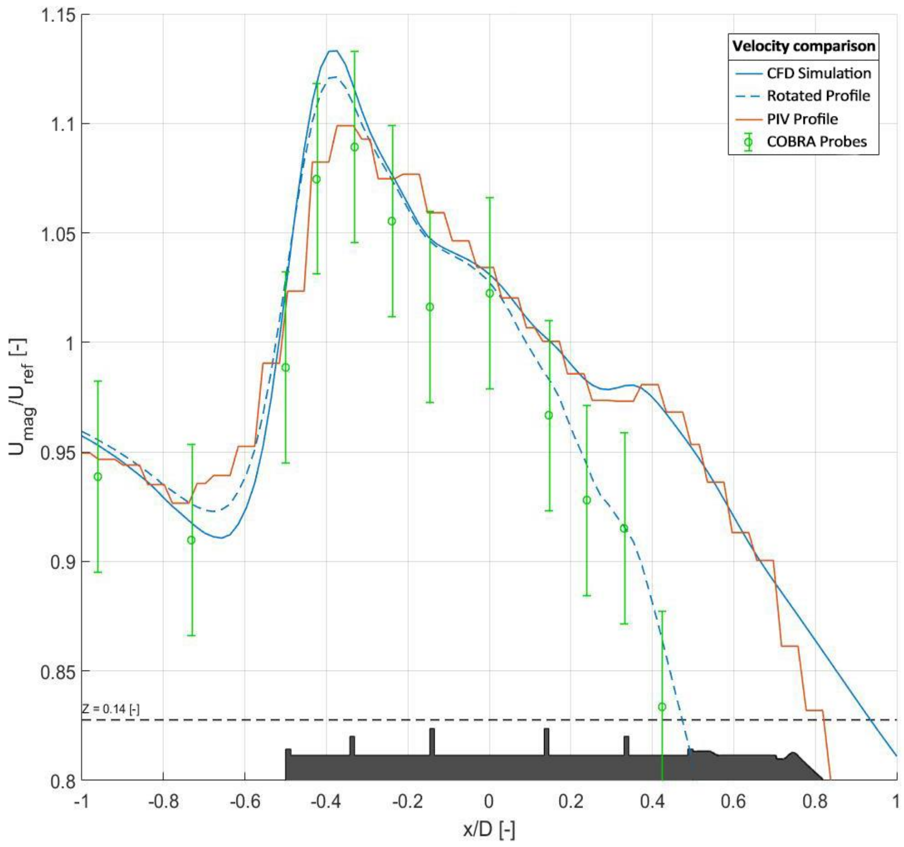
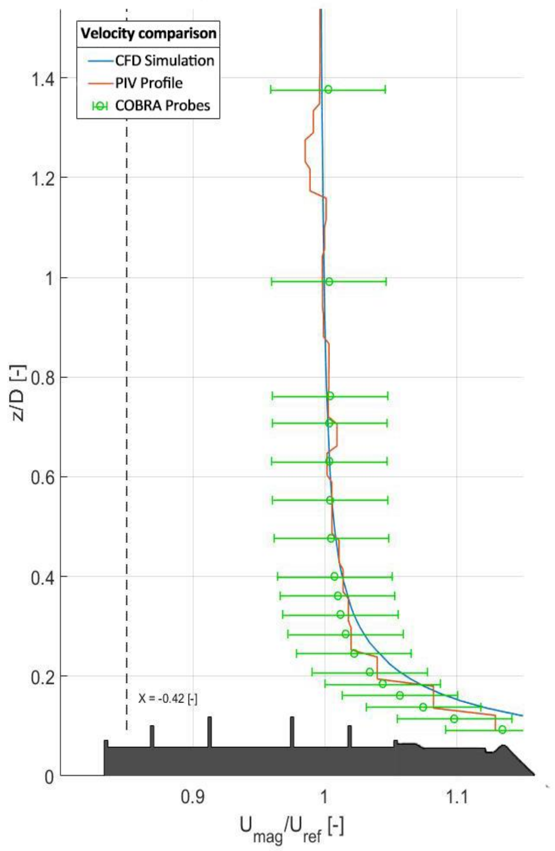
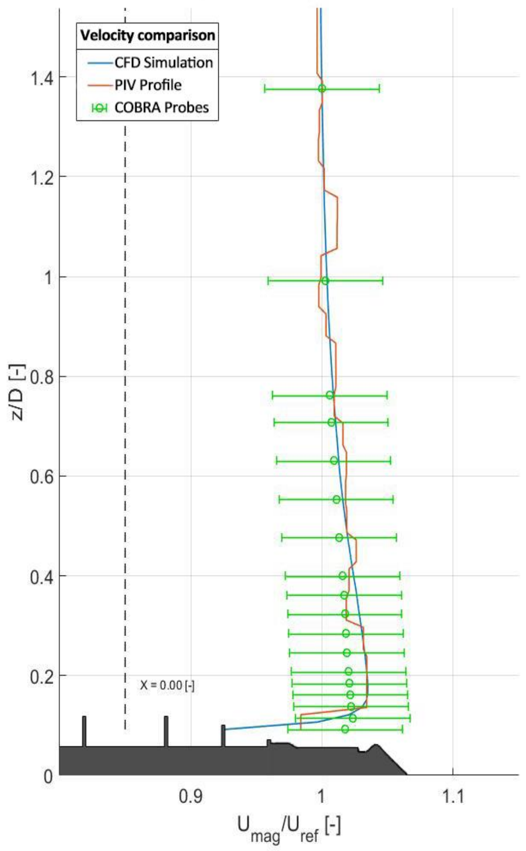
Once corrected for rotation the CFD profiles shows a very good agreement with experimental data







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The velocity fields are then used as an input in a Lagrangian particles tracking model to simulate the aerodynamic effect on hydrometeors

For each particle the motion can be described as:

$$V_p \rho_p \bar{\mathbf{a}_\mathbf{p}} = -C_D A_p \rho_a 0.5(\bar{\mathbf{v}_\mathbf{p}} - \bar{\mathbf{v}_\mathbf{a}}) \mid \bar{\mathbf{v}_\mathbf{p}} - \bar{\mathbf{v}_\mathbf{a}} \mid + V_p(\rho_p - \rho_a)\bar{\mathbf{v}_\mathbf{p}} - \bar{\mathbf{g}}$$

where the particles physical properties are obtained using literature correlations for solid precipitation.

Exponential parametrization

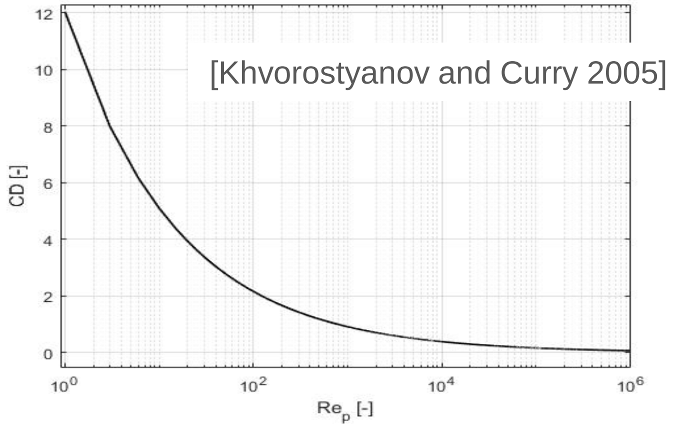
[Rasmussen 1999]

$$P_i = a_i \cdot e^{b_i}$$

Property	a_i	b_i
Density	0.017	-1
Area	0.785	2
Volume	0.524	3

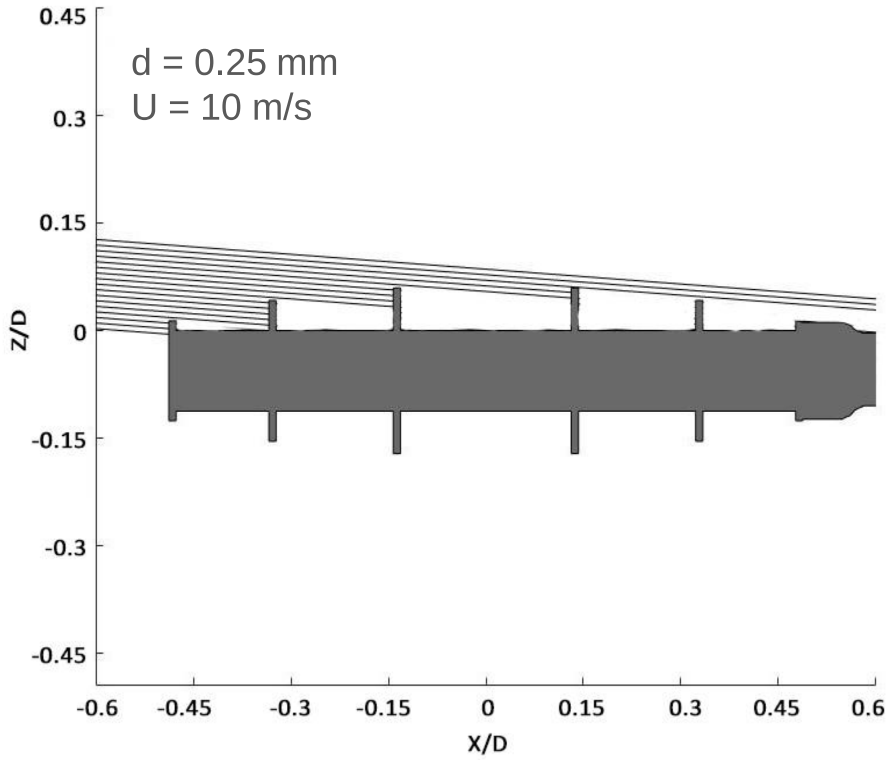
Drag coefficient $C_D = C_D(Re_p)$

with Re_p the particle Reynolds number

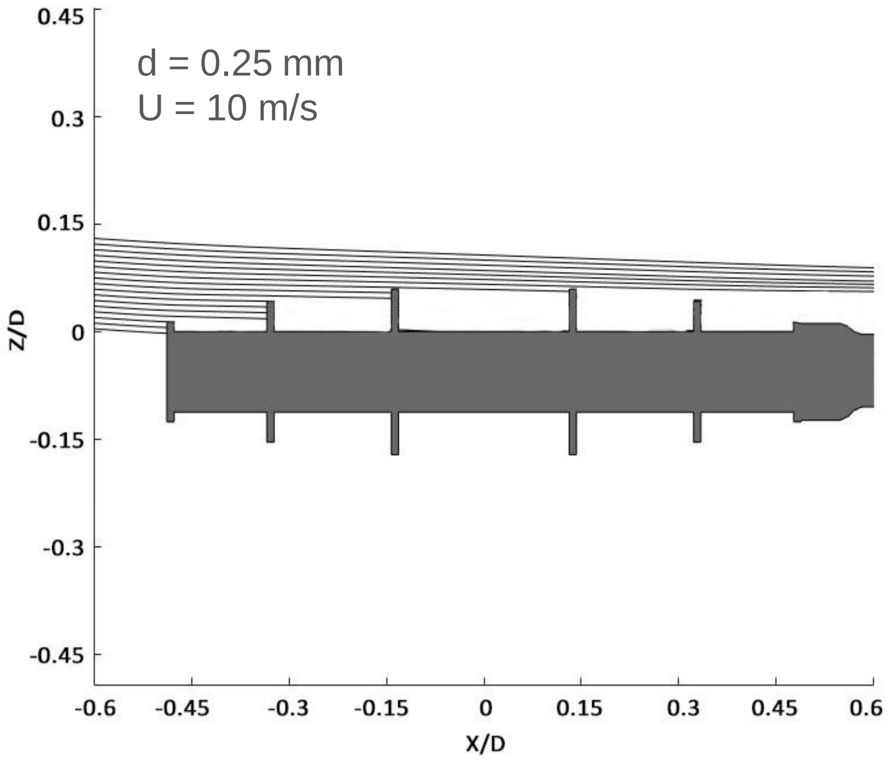


In total 11 diameters were tested,0.25, 0.5, 0.75, 1, 2, 3, 4, 5, 6, 7 and 8 mm using constant velocity fields (undisturbed by the instrument) and simulated velocity fields

Trajectories under constant velocity field



Trajectories under simulated velocity field



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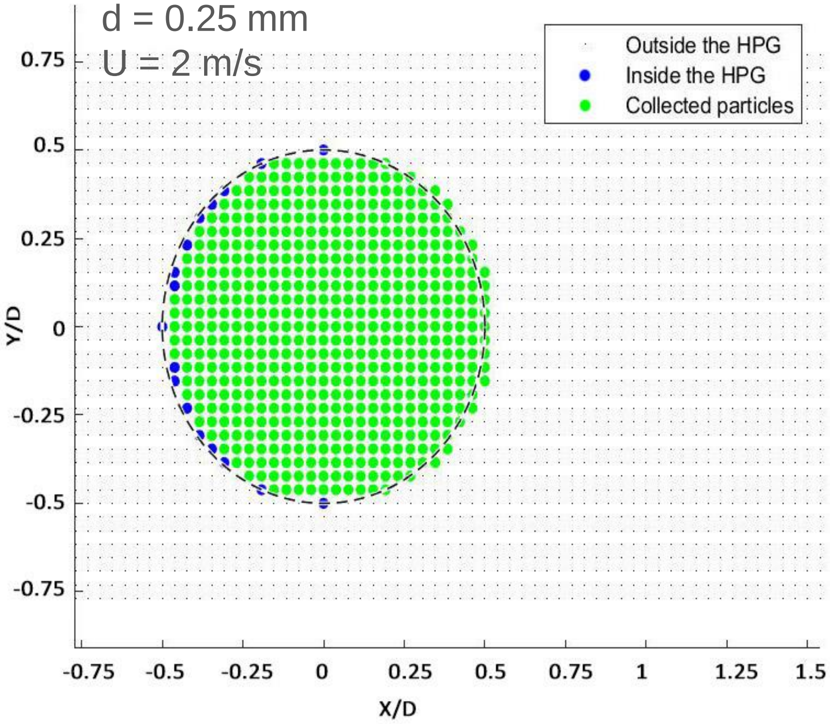
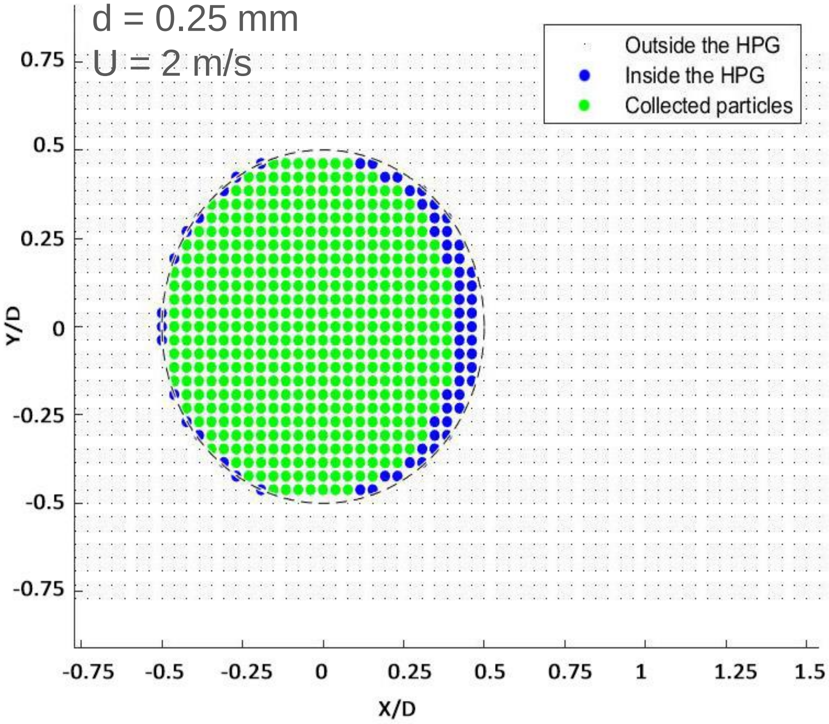
A large number of trajectories were simulated to establish if they are collected by the Hotplate or not.

Particles in green are collected while particles in blue should have been collected but are not collected.

Constant velocity field



Simulated velocity field



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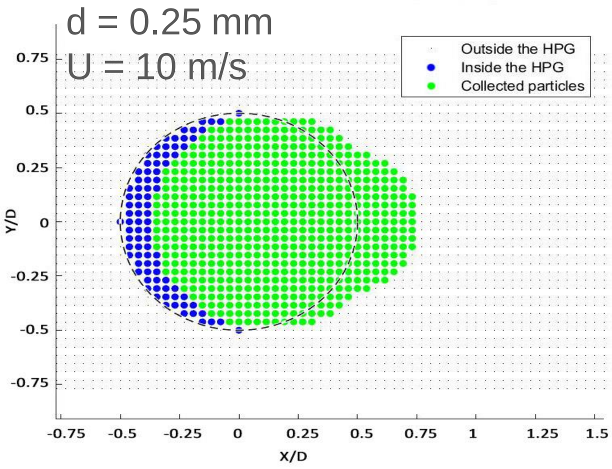
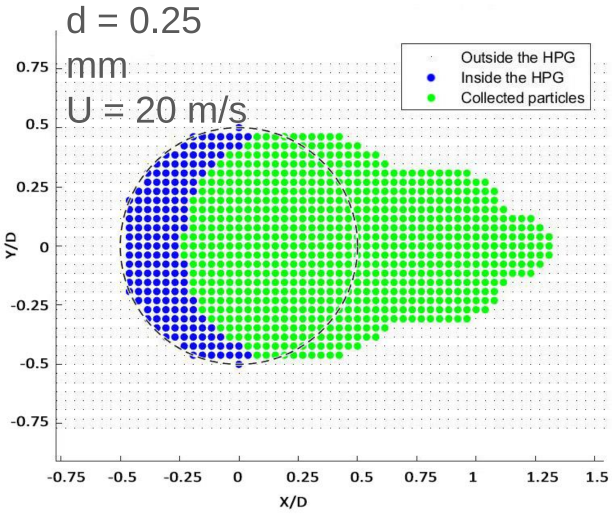
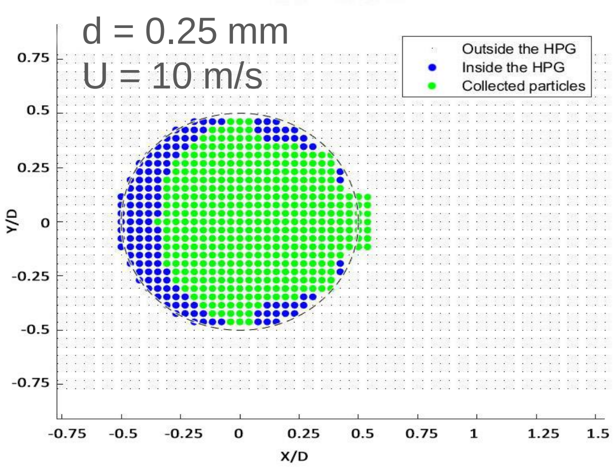
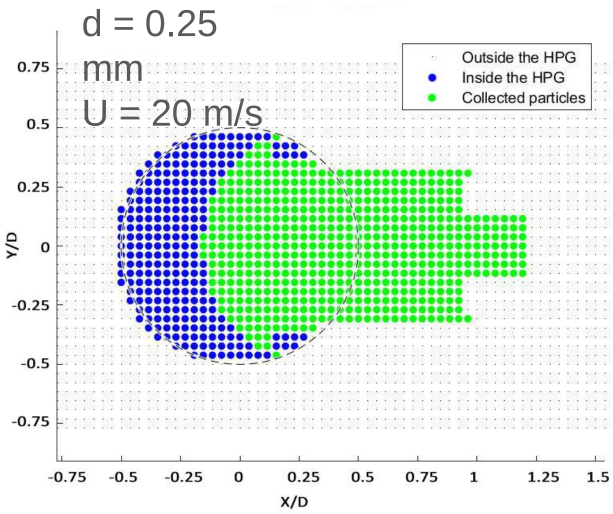
Constant velocity field





Simulated velocity field





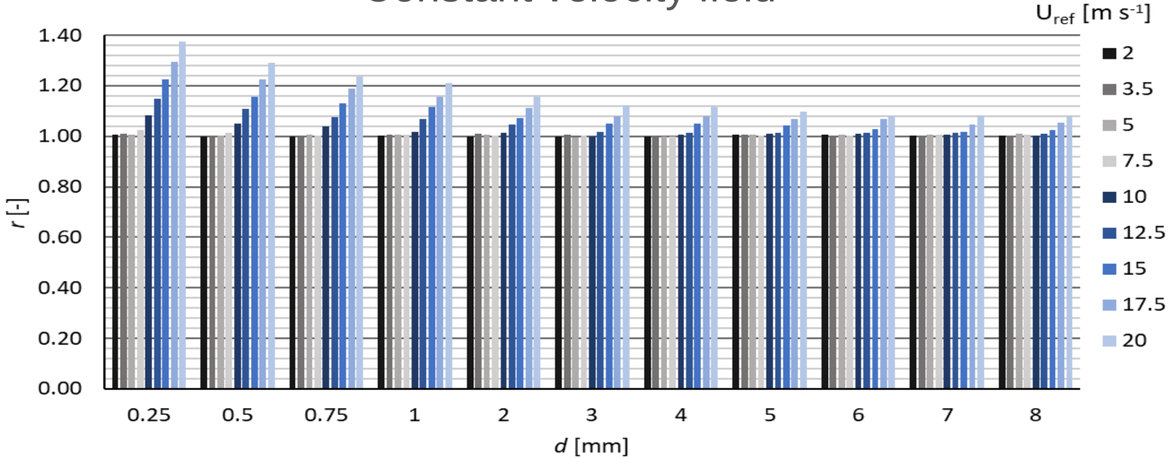
The peculiar shape of the Hotplate produces an overcatch that increases with increasing the wind speed

The aerodynamic effect of the instrument diverts a large number of particles producing undercatch

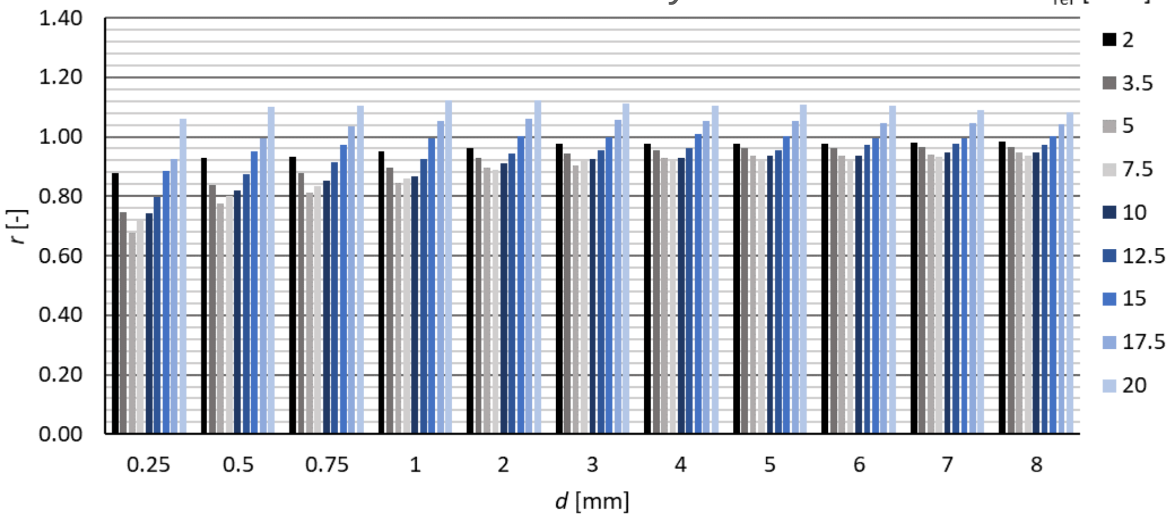
For very high wind speed the overcatch becomes significant

At high wind speed, the aerodynamic effect is less impacting than the geometric effect and the Hotplate shows an overcatch

Constant velocity field



Simulated velocity field



The catch ratio (r) was calculated for both simulated velocity fields and interpolated velocity fields and is defined as the ratio between the number of particles effectively collected and the number of particles that would have crossed the projection of the instrument collecting area if the Hotplate was not present

$$r(d,U) = \frac{N_{catched}(d,U)}{N_{teor}(d,U))}$$

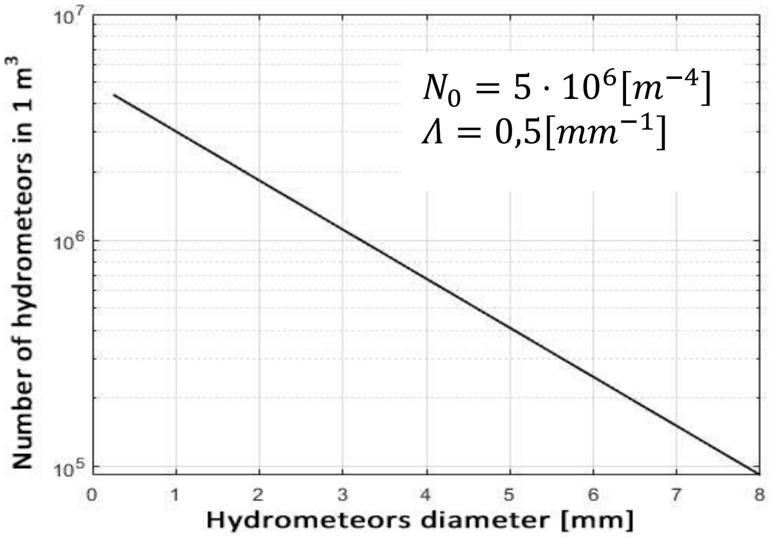
From the catch ratios, the collection efficiency can be obtained after defining the particle-size distribution (PSD)

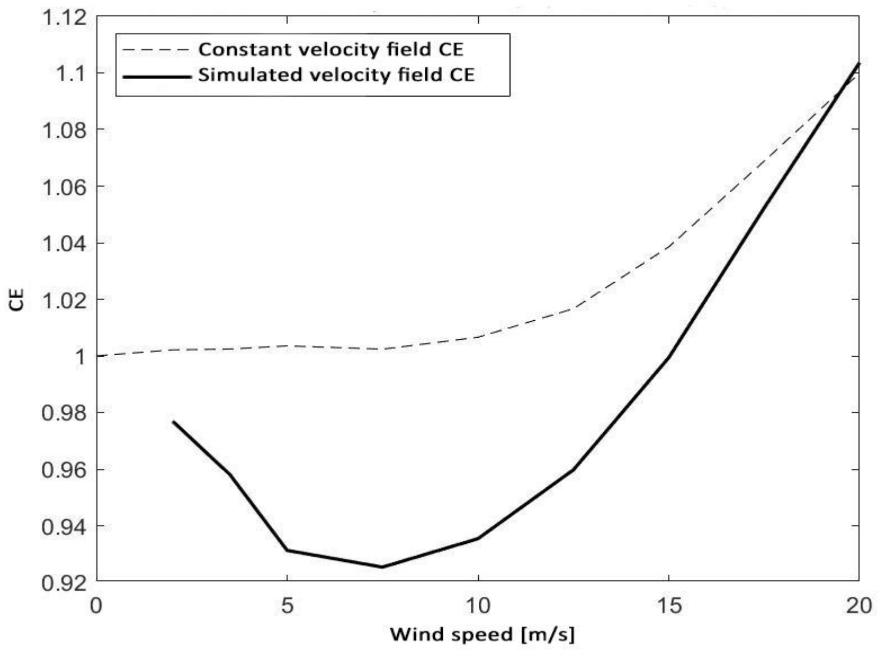
$$CE(U) = \frac{\int_0^{d_{MAX}} V(d_p) n_{catched}(d_p, U) N(d) dd_p}{\int_0^{d_{MAX}} V(d_p) n_{ideal}(d_p, U) N(d) dd_p}$$

Particle-size distribution

[Marshall-Palmer 1948]

$$N(d) = N_0 \cdot e^{-\Lambda d}$$





The collection efficiency curve for the Hotplate presents a very interesting behaviour, different from traditional gauges.

This is due to the gauge shape, especially the rings that prevent precipitation to slide off the plate, that increases the number of collected particles in case of high wind speed

Conclusions

The simulated effect of wind on the Hotplate precipitation gauge highlights the role of the particular geometry of the instruments on the catch performance.

The collection efficiency curve can be used to correct real-world measurements by using wind velocity observations alone as the ancillary variable required to perform the adjustment.

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