An example of computational approach used for aerodynamic design of a rain disdrometer

Un exemple de méthode de calcul utilisée pour le dessin aérodynamique d'un disdromètre de pluie

EMAD HABIB, *Graduate Research Assistant, Iowa Institute of Hydraulic Research, The University of Iowa, Iowa City, IA, 52242 USA*

WITOLD F. KRAJEWSKI, *Professor, Iowa Institute of Hydraulic Research, The University of Iowa, Iowa City, IA, 52242 USA*

ABSTRACT

The present work reports on the application of a computational fluid dynamics-based method as a tool to improve the aerodynamic design of rainfall measurement devices. The focus is on a new instrument, a two-dimensional video disdrometer that provides information about raindrop size distribution. The distorted wind field around and inside the instrument's body is simulated using a three-dimensional numerical model. A modified geometry of the instrument, suggested for operational purposes, is tested numerically. Trajectories of raindrops are simulated to investigate the wind effect on the catchment efficiency of the instrument. A stochastic Lagrangian particle-tracking model that accounts for the turbulence effect is examined. General guidelines related to aerodynamic aspects of the design of *in-situ* rainfall measuring devices are discussed.

RÉSUMÉ

Ce travail présente une application d'une méthode utilisée pour l'amélioration du dessin aérodynamique des instruments de mesures de pluie. Cette méthode est basée sur une technique de calcul de dynamique des fluides. L'étude se focalise sur l'utilisation d'un nouvel instrument, le vidéo-disdromètre deux-dimensions, qui restitue des informations sur la distribution granulométrique des gouttes de pluie. Le champ de vent modifié dans le corps et autour de l'instrument est simulé à l'aide d'un modèle numérique à trois dimensions. Un dessin modifié de l'appareil, suggéré pour des fins opérationnelles, est testé numériquement. Les trajectoires des gouttes de pluie sont simulées pour tester l'effet du vent sur l'efficacité de capture de l'appareil. Un modèle stochastique Lagrangien qui tient compte de l'effet de la turbulence sur les trajectoires simulées est examiné. Des guides généraux relatifs aux aspects aérodynamiques du dessin des instruments de mesure de pluie in-situ sont discutés.

Introduction

Knowledge of precipitation amount and distribution is essential for hydrologic prediction and a wide range of engineering design applications. In addition to rainfall quantities, commonly obtained using rain gauges, information about raindrop size distribution (DSD) is also valuable. DSD is needed to develop rainfall estimation algorithms based on remote sensing measurements. A recent instrument specially designed for DSD measurements is the 2-D video disdrometer developed by Joanneum Research, Austria [3]. The device has given impetus to several basic investigations in atmospheric research (e.g. [5], [8]). Recently, the disdrometer was operated in several NASA-sponsored field experiments in Florida, Brazil, and Marshall Islands in 1998-99.

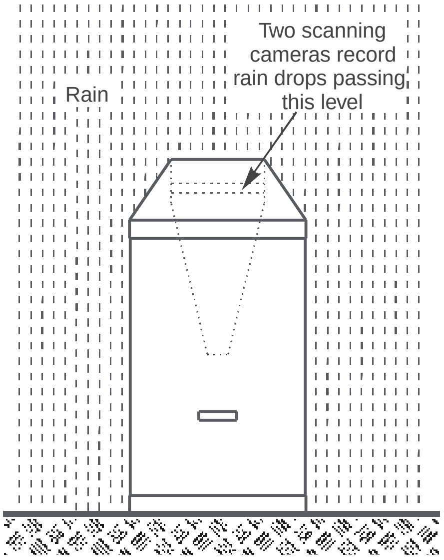

Fig. 1. 2-D Video disdrometer: sensor unit containing cameras and light sources.

In-situ measurements of rainfall are subject to the wind effect-a major source of errors [7]. Similar to common rain gauges, the 2-D video disdrometer body causes distortion of the wind field resulting in modified trajectories of the raindrops. This leads to a reduction in the catchment efficiency of the instrument. The authors discuss the potential use of a computational fluid dynamics (CFD) technique that can be used for quantification and correction of wind-related rainfall measuring errors. The focus is on the effect of a proposed modification to the geometry of the device.

Methods and analysis

2-D Disdrometer

Fig. 1 shows the 2-D video disdrometer in its original design. The main (sensing) unit has a rectangular base and a height of 0.96 m. The unit is opened at the top which has inclined sides. Inside, two line-scanning cameras record the falling raindrops; detailed description is given in [3]. Field deployment of the disdrometer also requires the use of an outdoor computer unit. Recent field experi-

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ments in Florida witnessed the failure of the outdoor computer due to the high temperature and humidity in the tropics. To fix the problem, the device was modified by consolidating the outdoor computer and the sensing unit with an air conditioner-all in one enclosure. As a result, the geometry of the unit has been substantially changed making the entire structure twice as large as the original unit. This causes a concern about the increased wind flow deformation around the unit and in the vicinity of its orifice. In an attempt to reduce the wind effect, a cylindrical geometry of the sensing unit with a funnel-like orifice at the top is considered (Fig. 2). The orifice's shape and size were kept unchanged to not disturb the optical and electronic components of the instrument.

Wind flow simulation

To evaluate the wind effect on the performance of the disdrometer, three-dimensional simulations of the airflow around and inside its body were performed. This was achieved using FLUENT/UNS-4.2, a general CFD software developed by Fluent Inc. [2]. The software solves the flow governing equations, mass and momentum, using a control-volume discretization scheme. A standard κ-ε turbulence closure is adopted; further details are available in the software manual [2] and many other references (e.g., [6]). Fig. 2 shows the computational grids designed to represent the disdrometer geometric details of the original rectangular and the modified cylindrical orifice designs. Several flow conditions were simulated to evaluate the original and modified designs based on how much flow disturbance and distortion they introduced. As an illustrative example, Fig. 3 shows the results of a simulation case for both designs where, for space limits, only contours of the horizontal velocity component are displayed. In this simulation, the airflow was initialized with a purely horizontal velocity of 1 m/s, which corresponds to a simplified situation of an instrument-free domain. The velocity contours for the original design (Fig. 3-a) show a complex flow field around and inside the disdrometer with a significant distortion of the wind pattern. A shear layer with high velocity gradients formed above the disdrometer orifice. Also, a three-dimensional vortex intersecting the recording cameras slots formed inside the orifice. It was also noticed that high vertical velocity components were generated in the vicinity of the orifice due to the obstruction of the flow by the disdrometer body. Similar flow patterns were reported in [5].
Compared to the original design, the new geometries (Fig. 3-b) show similar flow features. However, changing the geometry of the disdrometer from rectangular to a cylindrical shape helps to mitigate the flow field distortion. This can be seen in Fig. 4 which compares vertical velocity profiles, drawn along the instrument orifice level, for the two designs. With the new geometries, the instrument orifice is now free from the high vertical velocity components that were present in the original design. Also, the strength of the vortex that intersects the cameras recording plane is significantly weakened. Given the restrictions imposed by the existing instrument and its electronic/optical components, the modified design can be considered an improvement that helps to reduce the wind effect.

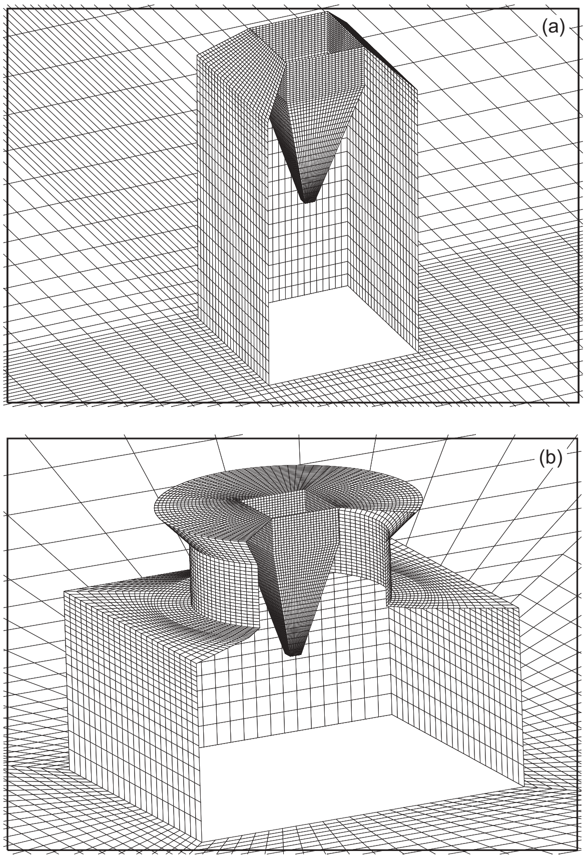

Fig. 2. Computational grid: (a) original, (b) modified designs of the disdrometer.

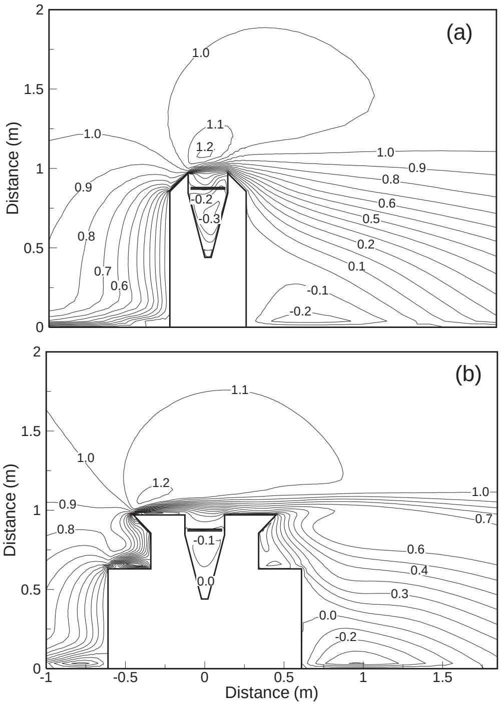

Fig. 3. Contours of horizontal velocity component (m/s): (a) original, (b) modified designs. Instrument-free horizontal velocity of 1 m/s is used to initialize the flow field.

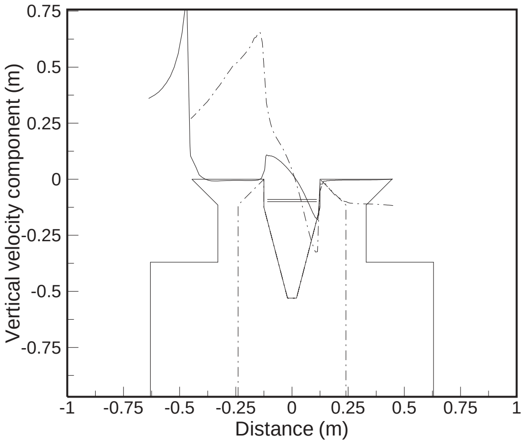

Fig. 4. Comparison of vertical velocity profiles: original (dashed line), and modified (continuous line) designs.

Assessment of the wind effect on the device catchment efficiency

The deformation of the wind field observed with both of the original and the modified designs affects the trajectories of the falling drops resulting in reduced measurement efficiency. Nešpor and Sevruk [4] proposed a comprehensive procedure that can be used to quantify such reduction. Implementing this procedure, or an alternative one, is out of the scope of our study. Instead, an illustrative investigation is conducted to explore some of the issues associated with the assessment of efficiency reduction. This requires the simulation of the movement of raindrops. Following a Lagrangian approach, discrete particles are released into the flow and tracked by integrating the particle equation of motion. Since raindrops have a much higher density than the surrounding air, only drag and gravity-buoyancy forces were considered yielding a simplified form of the equation of motion:

$$\frac{\pi}{6} d^3 \rho_p \frac{d\vec{U}_p}{dt} = 3\pi\ \mu\ d(\vec{U}_f - \vec{U}_p) + \frac{\pi}{6} d^3 (\rho_p - \rho_f)\vec{g} \qquad (1)$$

In (1) d is the droplet diameter, U_f, U_p, and ρ_f, ρ_p are the velocities and densities of the fluid and the rain droplet, respectively, μ is the fluid viscosity, and g is the acceleration of gravity. For a given droplet diameter, initial position, and velocity, the trajectory of an individual droplet can be computed by integrating (1). First, the trajectories were simulated using the mean flow only. Fig. 5(a) shows an example of the computed trajectories for raindrops of 0.5 mm diameter released in a wind field initialized to a horizontal velocity of 1 m/s. The trajectories maintain uniform and straight path until they approach the instrument orifice where they get deformed and deflected. The strong shear layer and the increased vertical velocity component near the instrument orifice are responsible for such deformation.

Effect of turbulence on trajectories of raindrops

The turbulent features of the simulated airflow flow, as represented by the turbulent kinetic energy, κ, and its dissipation rate, ε, (plots not included), indicated high levels of turbulence production and dissipation above and inside the disdrometer orifice. To include the turbulence effect, trajectories need to be simulated using both the mean flow and its turbulent quantities. Therefore, one can consider the instantaneous flow velocity as a sum of a time-averaged value, available from the mean flow simulations, and a fluctuation component. The velocity fluctuation component was simulated using a stochastic model adopted in many industrial and environmental applications [1]. In this model, a velocity fluctuation component, u´, is assumed to have a normal distribution with zero mean and standard deviation related to the turbulent kinetic energy κ: $u' \sim N\ (0, \sqrt{\tfrac{2}{3}\kappa})$. The random value of u´ is considered to affect a tracked particle for an interval of time that is proportional to the ratio κ/ε. For each integration time step of (1), the values of κ and ε are obtained from the results of the mean airflow simulations and used to generate u´. Fig. 5(b) shows the trajectories of the same drops of Fig. 5(a) computed with the stochastic tracking model. A significant difference is apparent between the two tracking procedures. The trajectories computed using the stochastic model showed pronounced irregularity and deformations compared to the mean flow case. The distribution and number of drops crossing the sensing area is affected by the turbulent eddies near and inside the device orifice. This indicates the importance of including the effect of the random turbulent flow features in the trajectory computations. A more pronounced effect of the turbulence was reported by Nešpor et al. [5] who showed that small raindrops might even loop inside the instru-

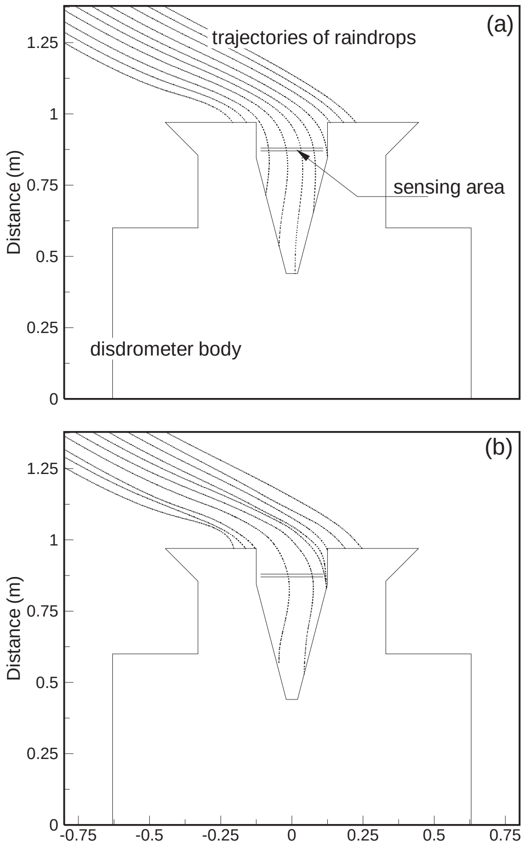

Fig. 5. Simulated trajectories of raindrops: (a) computations based on mean flow only, (b) turbulence effect included.

ment. However, Nešpor et al. [5] used a different tracking model [4] in which the turbulence effect was assumed to have an averaged influence.

The differences observed in the simulated trajectories, compared to the mean flow case and to the results of [5] indicate the critical need to validate the proposed tracking models. The lack of relevant observations of individual raindrops under the effect of turbulent wind flow makes it difficult to examine the assumptions of the tracking model and its mechanism that accounts for the turbulence effect. Therefore, field and laboratory observations of raindrop trajectories are needed to help understand these complex processes and to provide more reliable and realistic modeling techniques.

Discussion and concluding remarks

The present study confirms the potential of CFD-based design of rainfall measuring devices. The applied approach enabled to modify the geometric design of a new instrument, the 2D-video disdrometer, so that the wind effect on its catchment efficiency can be minimized. The results of the flow simulations can be used to develop some basic design guidelines for future use. The instrument height should be as low as possible so that the airflow distortion by its elevated structure is minimum. Circular/cylindrical geometries should be used to eliminate the angular dependence in windy conditions. The structure of the device should allow airflow around and below the instrument so that interference with the sensing area is minimal. The proposed CFD approach enables testing variety of designs in a fast and computationally inexpensive way. Accordingly, it is recommended to incorporate such simulations, as a standard procedure, in future designs of other similar rainfall measuring devices.

In an attempt to quantify the reduction in the catchment efficiency, the study showed the difficulties involved with the simulation of raindrops trajectories. In particular, it is not clear how to correctly model the effect of turbulence on the movement of the raindrops. In this study, the authors applied a stochastic particle-tracking model where significant differences in the simulated trajectories of raindrops were observed as compared to the mean flow effect. A comparison with earlier results showed qualitative differences in the simulated trajectories of raindrops and their behavior under the effect of turbulence. This strongly demonstrates the need for field and laboratory observations to validate any adopted tracking model and test its ability to reproduce the movement of raindrops.

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Notations

d	droplet diameter
U_f	fluid instantaneous velocity
U_p	particle instantaneous velocity
ρ_f	fluid density
ρ_p	particle density
μ	fluid viscosity
g	acceleration of gravity
u'	fluid fluctuating velocity component
κ	turbulent kinetic energy
ε	turbulent kinetic energy dissipation rate

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