Building and Environment 81 (2014) 283–295

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Numerical simulations of wind-driven rain on an array of low-rise cubic buildings and validation by field measurements

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ARTICLE INFO

Article history:
Received 2 June 2014
Received in revised form
5 July 2014
Accepted 8 July 2014
Available online 18 July 2014

Keywords:
Wind-driven rain
Validation
Computational fluid dynamics (CFD)
Eulerian multiphase model
Turbulent dispersion

ABSTRACT

The relation between wind-driven rain (WDR) and its potential negative effects on the hygrothermal performance and durability of building facades can be better understood by the correct estimation of the spatial and temporal distribution of the WDR intensity. Computational Fluid Dynamics (CFD) simulations with Eulerian Multiphase (EM) modeling are used to obtain accurate spatial and temporal information on WDR. The EM model has the advantage of predicting the WDR intensity on all surfaces of a complex geometry within the domain at once. There is a lack of numerical studies on the WDR intensity in generic and idealized multi-building configurations. In this paper, WDR intensities on an array of 9 low-rise cubic building models for wind from three different wind directions are estimated numerically using the EM model including the turbulent dispersion of raindrops. The numerical results are validated by comparing the calculated catch ratio values with data from field measurements in Dübendorf, Switzerland after two rain events with different characteristics. The CFD simulations successfully estimate the WDR intensities at the positions of 18 WDR gauges for both rain events. The influence of turbulent dispersion is found to be lower than 3% for both rain events. It is found that, for oblique wind directions, even though the maximum WDR intensity on the facades is lower, the whole building is exposed to up to 57% more WDR.

1. Introduction

Wind-driven rain (WDR) is rain with a horizontal velocity component due to its co-occurrence with wind. WDR is one of the most important moisture sources that influence the hygrothermal performance and the durability of building facades. It can lead to several undesired phenomena in building physics such as frost damage at exterior wall surfaces [1–3], erosion of building materials [4,5], moisture induced salt migration [2,6], discoloration by efflorescence [2], surface soiling [7,8] and mold growth at interior wall surfaces [9].

Three methods exist for estimating the WDR intensity on building surfaces: (1) measurements, (2) semi-empirical methods and (3) numerical simulations with Computational Fluid Dynamics (CFD). Blocken and Carmeliet [10,11], Blocken et al. [12] and Blocken [13] provided extensive reviews of WDR research in building physics. Generally, measurements of WDR on building facades are difficult, time-consuming and prone to errors [14–16]. They are also confined to the meteorological conditions present at the time of experiments. Semi-empirical methods, on the other hand, are fast and easy to use but they only give approximations of the WDR intensity and they cannot provide detailed information. The impinging WDR intensity is governed by several parameters, such as building geometry, environment topography, position on the building facade, wind speed, wind direction, rainfall intensity and raindrop-size distribution [17]. The semi-empirical methods are unable to reliably take all of these effects into account [3,14,18]. Therefore, semi-empirical methods are generally suitable only for stand-alone buildings in simple configurations, or for preliminary analysis. CFD simulations have the advantage of providing detailed spatial and temporal WDR distributions on complex building geometries. Furthermore, CFD simulations can give detailed information on the rain drop impact speed and impact angle on the facade, which can later be used to determine the droplet physics after impact, such as bouncing, splashing, spreading and film forming. These phenomena are particularly important to distinguish in building envelope heat-air-moisture (BE-HAM) transport models, where WDR intensity is used as a main boundary condition [12,19–21].

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http://dx.doi.org/10.1016/j.buildenv.2014.07.008

A steady-state numerical simulation technique for WDR was developed by Choi [22–25] by combining the Reynolds-Averaged Navier-Stokes (RANS) equations and Lagrangian Particle Tracking (LPT). Several researchers applied similar models with LPT [8,17,26–34] on isolated buildings or on particular buildings in a geometrically complex environment. Blocken and Carmeliet [17] extended Choi's simulation technique by adding the temporal component, allowing the determination of both the spatial and temporal distribution of WDR for transient rain events. Huang and Li [35] showed that the Eulerian Multiphase (EM) model with RANS can give accurate results for WDR on the windward facade of an isolated low-rise building. Kubilay et al. [36] performed a validation study with the EM model on a historical building with a monumental tower by comparing the results with measurement data and with numerical data from the LPT model. This study showed that the user time spent for the simulation of WDR on an isolated building decreases by at least a factor of 10 using the EM model compared to the LPT model. The turbulent dispersion of raindrops was implemented into the Eulerian Multiphase (EM) model for the mean WDR calculations by Kubilay et al. [37]. It was shown that taking turbulent dispersion into account reduces the deviation between CFD simulations and field measurements for a high-rise tower building.

In the present paper, a CFD validation study is performed on an array of low-rise cubic building models. CFD simulations using the EM model with turbulent dispersion of raindrops are performed to study the WDR intensity during two rain events. The validation of the numerical model is accomplished by comparing the results with the WDR measurement dataset provided by Kubilay et al. [3]. Section 2 presents the field measurement geometry and the measured rain event data for the validation study. In Section 3, the numerical model, the governing equations, the computational domain, the boundary conditions and the solver settings are described. Section 4 presents the results of the CFD simulations, the validation study and analysis of WDR on building models. Finally, Sections 5 and 6 provide a general discussion and conclusion, respectively.

2. Field measurements

The measurement setup is composed of 9 identical low-rise cubic building models. They are positioned in a regular array as shown in Fig. 1. The building models each have dimensions $H \times H \times H = 2 \times 2 \times 2\ \mathrm{m}^3$ and they are spaced $H = 2$ m apart. The total height of the models, with the wooden support beams below, is 2.17 m. The measurement setup is located on the campus of the Swiss Federal Laboratories for Materials Science and Technology (Empa) in Dübendorf in a suburban area located east of the city of Zurich, Switzerland, latitude 47°24′9″ and longitude 8°36′50″. The field measurements were performed between May 2013 and October 2013. A detailed description of the building and environment geometry and of the measurement results can be found in Kubilay et al. [3].

The WDR measurements are conducted on the west facades of cubes 2 and 8, indicated in gray in Fig. 1(a). These facades are instrumented with 9 WDR gauges each. The collectors of the WDR gauges are connected via tubing to tipping bucket mechanisms that are placed inside the building models. The reference measurements of wind speed and wind direction are conducted at a meteorological mast, located 3H (=6 m) west of the array of cubes. The horizontal rainfall intensity is measured by a rain gauge with tipping bucket mechanism positioned near the meteorological mast.

Fig. 2 shows two rain events that were measured on June 9–10, 2013 and September 16–19, 2013 [3]. The most important sources of measurement errors are the evaporation of adhesion water, E_{AW}, and the rest-water in the tipping bucket, E_{RW}. The relative errors, $E_{TOT} = (E_{AW} + E_{RW})/S_{wdr}$, where S_{wdr} is the total WDR amount registered by a WDR gauge during a rain event, are estimated (following the procedure in Kubilay et al. [3]) to be between 2.2% and 3.9% for the rain event on June 9–10, 2013 and between 14.8% and 34.2% for the rain event on September 16–19, 2013. The rain events with low measurement errors were selected for CFD validation in this study.

3. Numerical simulation

In the EM model, the rain phase is regarded as a continuum as is the air phase. Each class of raindrop size is treated as a different phase, as each group of raindrops with similar size will interact with the wind-flow field in a similar way.

3.1. Governing equations

In the present study, the wind-flow equations are solved using 3D steady RANS with the renormalization group (RNG) k–ε model [38]. Rain phase calculations are one-way coupled with the air phase. This is a valid assumption as the volumetric ratio of rain in air is below 1×10^{-3} for rainfall intensities up to 20 mm/h and below 1×10^{-2} for even the most severe cases according to the study by de Wolf [39] that provides the distribution density of raindrop diameters at different rainfall intensities. For each rain phase, the following continuity and momentum equations are solved separately:

$$\frac{\partial \alpha_k}{\partial t} + \frac{\partial\left(\alpha_k \overline{u}_{k,j}\right)}{\partial x_j} = 0 \quad \text{(no summation over } k\text{)} \qquad (1)$$

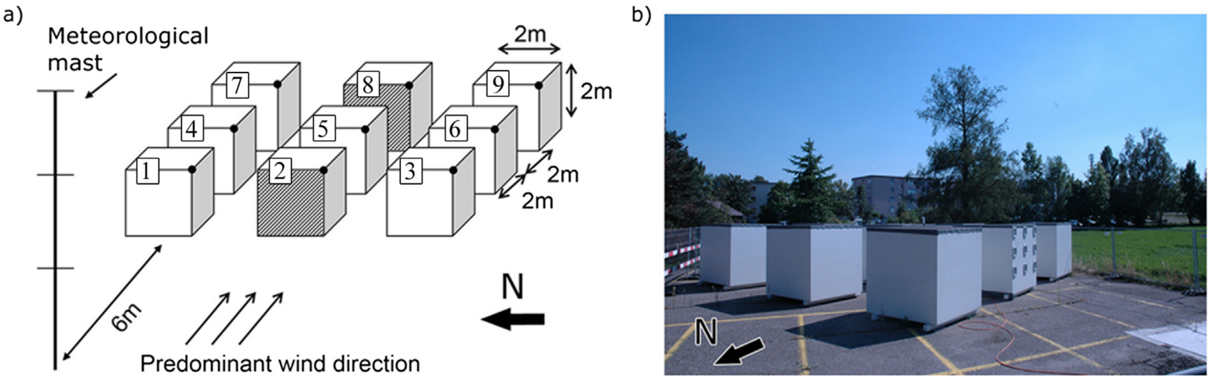

Fig. 1. a) Geometry of regular array of cubic building models. The WDR measurements are conducted on the gray facades. b) View from northwest of the measurement site.