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High-resolution field measurements of wind-driven rain on an array of low-rise cubic buildings

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ABSTRACT

Wind-driven rain (WDR) is one of the most important moisture sources with potential negative effects on the hygrothermal performance and durability of building facades. The impact of WDR on building envelopes can be understood in a better way when the WDR intensity distribution can be accurately predicted. Most field experiments of WDR reported in the literature focused on either stand-alone buildings or on buildings in geometrically complex environments. There is a need for high-resolution measurements in more generic and idealized multi-building configurations. The present study reports WDR measurements that were conducted with high spatial and temporal resolution in a test setup consisting of an array of 9 low-rise cubic building models, located in Dübendorf, Switzerland. Detailed descriptions are provided of the building models, the surroundings, the measuring instruments, the measurements of WDR, wind speed, wind direction, horizontal rainfall intensity and air temperature during three selected rain events, as well as error estimates for the WDR measurements. The datasets of rain events and WDR measurement results are made available online to download and are intended for WDR model development and validation.

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 surface soiling due to runoff, weathering, algae formation, salt damage and frost damage at exterior wall surfaces, and can be a source of moisture leading to mold growth at inside wall surfaces [1,2]. Information on WDR intensities is used as a main boundary condition in building envelope heat–air–moisture (BE-HAM) transport models, reinforcing the need for accurate information on the spatial and temporal distribution of WDR.

Different methods can be used to assess WDR intensities. Several studies have provided driving rain indices, which are an indication of the severity of exposure to WDR calculated from hourly, daily or monthly reference wind speed and reference rainfall intensity [3–6]. In some cases, these indices have been presented as driving rain maps [7–11]. Driving rain indices and driving rain maps can be useful to compare the severity of exposure to WDR at different geographical locations but they do not provide detailed spatial and temporal information on the WDR intensity impinging on building facades. The impinging WDR intensity is governed by a wide range of parameters, such as building geometry, environment topography, position on the building facade, wind speed, wind direction, rainfall intensity and raindrop-size distribution [12]. Methods to accurately assess the WDR intensity on building facades should therefore take into account these influencing parameters. In addition to driving rain indices, semi-empirical models have been established [13–18]. These models can provide information on the temporal variation of WDR but they often assume the moisture source due to WDR to be uniform across large parts of the facade. This can lead to large errors in simulations of moisture transport in the building envelope, as in reality, WDR intensity is far from uniform across the facade.

Computational Fluid Dynamics (CFD) simulations can be a valuable tool to estimate distribution of WDR intensities across

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facades [12,19–24]. However, development and validation of such numerical models require complete WDR measurement datasets, which follow strict guidelines in order to ensure their accuracy and reliability and to keep measurement errors small. Blocken and Carmeliet [14] state that an adequate experimental WDR dataset should comprise and/or be accompanied by the following information: (1) detailed descriptions of the building site, (2) the building geometry and (3) the measurement setup; (4) measurements of the reference wind speed, the reference wind direction and the horizontal rainfall intensity (i.e. the rainfall intensity through a horizontal plane) that have been conducted near the building site and in 'free-field' conditions (i.e. at a position that is not significantly influenced by the presence of the building); (5) WDR measurements at the facades with a sufficiently high resolution in space and time and (6) error estimates for the WDR measurements.

To the knowledge of the authors, up to now, field experiments of WDR focused on either stand-alone buildings or on a particular building in a geometrically complex environment. Lacy [25] showed that the WDR distribution varies considerably with the size of the building and shows a large variation across the building facade. Brown [26] conducted a WDR measurement study on a large number of buildings in Dorset, England. van Mook [27] presented WDR measurements on the main building of Eindhoven University of Technology in the Netherlands. This is a wide high-rise building surrounded by several other similar size buildings in a complex urban environment. Tang et al. [28] presented WDR measurements on the Cathedral of Learning on the University of Pittsburgh campus. This is a rather complex high-rise building that is surrounded by several lower buildings. Blocken and Carmeliet [14] performed WDR measurements on the south-west facade of the VLIET test building in Leuven, Belgium, which is a stand-alone low-rise building composed of three sections: sloped-roof section, flat-roof section with roof overhang and flat-roof section without roof overhang. Nore et al. [29] presented WDR measurements on a low-rise test building located near two other similar size buildings in Trondheim, Norway. Ge and Krpan [30] presented measurements on a wide low-rise building with roof overhang in British Columbia. Finally, Briggen et al. [21] performed WDR measurements on the tower of a historical building, St. Hubertus Hunting Lodge, located in the Netherlands.

For detailed model validation, there is a need for high-resolution measurements in more generic and idealized multi-building configurations. Therefore, the present study reports a WDR measurement dataset with high spatial and temporal resolution for a setup consisting of a regular array of 9 low-rise cubic building models of 2 m height each. The building models are manufactured so that the measurement setup is adjustable and can be rearranged at a later stage to represent different urban configurations. In multi-building environments, the wind flow is influenced by other buildings or objects in the vicinity, which will have an impact on the WDR intensities. In an urban environment with an array of low-rise cubic buildings, there are regions where the flow between the buildings is weakly coupled with the free stream flow. These are the recirculation regions where the wind speed values are low. In past research, it has been shown that the effect of turbulent dispersion of raindrops becomes important for cases where smaller droplets travel parallel to the building facade at low wind speed values [2]. Furthermore, Blocken et al. [31] showed that, by upstream and downstream disturbances, buildings have mutual influence on their WDR exposure. The present study involves a relatively high number of WDR gauges with high WDR acquisition resolution that aims to measure and compare spatial distribution of WDR intensity on the facades of different buildings in an urban multi-building configuration.

In the present paper, Section 2 presents the buildings, the surrounding site, the measuring equipment and the error analysis. Section 3 presents the measurement data of three carefully selected rain events. Section 4 estimates the WDR intensities by semi-empirical models and compares the results with the experimental data. Section 5 provides a discussion on the experimental WDR results. Finally, Section 6 provides the conclusions.

2. Measurement setup

2.1. Buildings and surrounding site

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 aim to study the WDR intensities for a regular array of 9 identical low-rise cubic building models, as shown in Fig. 1(a). The models have dimensions $H \times H \times H = 2 \times 2 \times 2$ m^3 and they are spaced $H = 2$ m apart from each other. The cubes are made of wood panels on a wood structure and finished with protective paint. The roofs are flat and covered with a water resistant polymeric membrane as roofing. The cubes are placed on an asphalt parking lot, and positioned on pavement blocks and wooden bars for further protection and convenience of relocation. The wooden bars have been placed so that they prevent airflow under the cubes for wind from west. The total roof height including the support beneath the cubes is 2.17 m.

In Fig. 1(a), the southwest top corners of the cubes are indicated with dots. Preliminary analysis of the local meteorological data indicates that the main wind direction, from where the most WDR is obtained, is west. The measurements are conducted on the west facades of cubes A and B, indicated in grey in Fig. 1(a). Fig. 1(b) shows a view of the setup from northwest and Fig. 1(c) shows a plan view of the measurement site. The measurement site has an open field with short grass at the south-west of the setup. In west direction, the field is about 35 H long and, further upstream, high trees and buildings are present. In south direction, the field is about 65 H long and, further upstream, high-rise buildings and a motorway are present. From northwest to east, there are several nearby low-rise and high-rise buildings. The closest of them are located at about 10 H distance from the experimental setup to northwest and northeast.

2.2. Measurement equipment

The wind speed, the wind direction, the wind elevation, the air temperature and the horizontal rainfall intensity are recorded in addition to the WDR in order to provide the required data to allow analysis of the WDR process and to provide representative validation data for possible numerical simulations. Wind direction is the azimuth angle from north. Wind elevation is the angle of the wind velocity vector with the horizontal plane.

2.2.1. Wind measurements

In order to measure the approach-flow wind direction and wind speed, a meteorological mast is positioned west of the measurement site (see Fig. 1(c)). The measurement site is located within an internal boundary layer where the approach flow profile is still developing. Thus, the position of the mast has to be chosen as close as possible to the setup to catch the most representative approach-flow boundary layer profile. However, at the same time, its location should be outside the region influenced by the cubes themselves in order to measure the unobstructed free-field wind profile. The position of the mast is chosen to be at 3H = 6 m away from the array