Building and Environment 84 (2015) 170–180

Contents lists available at ScienceDirect

Building and Environment

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

Impact, runoff and drying of wind-driven rain on a window glass surface: Numerical modelling based on experimental validation

B. Blocken [a], [b], [*], J. Carmeliet [c], [d]

[a] *Building Physics and Services, Department of the Built Environment, Eindhoven University of Technology, P.O. box 513, 5600 MB Eindhoven, The Netherlands*
[b] *Division of Building Physics, Department of Civil Engineering, Leuven University, Kasteelpark Arenberg 40 - box 2447, 3001 Leuven, Belgium*
[c] *Laboratory for Building Science and Technologies, Swiss Federal Laboratories for Materials Testing and Research, Empa, Überlandstrasse 129, CH-8600 Dübendorfmailto, Switzerland*
[d] *Chair of Building Physics, Swiss Federal Institute of Technology ETHZ, ETH-Hönggerberg, CH-8093 Zürich, Switzerland*

ARTICLE INFO

Article history:
Received 31 July 2014
Received in revised form
30 October 2014
Accepted 5 November 2014
Available online 15 November 2014

Keywords:
Wind-driven rain
Driving rain
Wind flow
Runoff
Raindrop
Drying

ABSTRACT

This paper presents a combination of two models to study both the impingement and the contact and surface phenomena of rainwater on a glass window surface: a Computational Fluid Dynamics (CFD) model for the calculation of the distribution of the wind-driven rain (WDR) across the building facade and a semi-empirical droplet-behaviour model. The CFD model comprises the calculation of the wind-flow pattern, the raindrop trajectories and the specific catch ratio as a measure of the WDR falling onto different parts of the facade. The droplet-behaviour model uses the output of the CFD model to simulate the behaviour of individual raindrops on the window glass surface, including runoff, coalescence and drying. The models are applied for a small window glass surface of a two-storey building. It is shown that by far not all WDR that impinges on a glass surface runs off, due to evaporation of drops adhered to the surface. The reduction of runoff by evaporation is 26% for a typical cumuliform rain event and 4% for a typical stratiform rain event. These models can be used to provide the knowledge about WDR impact, runoff and evaporation that is needed for the performance assessment of self-cleaning glass or the study of the leaching of nanoparticles from building facades.

1. Introduction

Wind-driven rain (WDR) is one of the most important moisture sources affecting the hygrothermal performance and the durability of building facades (e.g. Refs. [1,2]). Consequences of its destructive properties can take many forms. Moisture accumulation in porous materials can lead to water penetration, moisture induced salt migration, discolouration by efflorescence, structural cracking due to thermal and moisture gradients, to mention just a few. WDR impact and runoff are also responsible for the appearance of other types of surface soiling patterns on facades that have become characteristic for so many of our buildings (e.g. Refs. [1,2]). Other types of WDR related problems include the self-cleaning action of glass combined with runoff [3] and the leaching of nanoparticles from surface coatings and biocides from facades [4–6].

In building physics, two parts of WDR research can be distinguished [2]: (1) assessment of the impinging WDR intensity (Figs. 1a and 2) assessment of the response of the building facade to the impinging WDR (Fig. 1b). The impinging WDR intensity is the total amount of rainwater that comes into contact with the building surface. What happens at and after impact/impingement is the focus of the second part of WDR research. It comprises the study of contact and surface phenomena such as splashing, bouncing, adhesion, runoff, evaporation, absorption and the distribution of the moisture in the facade (rain penetration and wetting-drying). It also includes the wide variety of rainwater penetration mechanisms such as hydrostatic pressure, wind pressure, surface tension and gravity.

Most WDR research in building physics in the past has focused on the first part. An extensive review of this part of WDR research was provided by Blocken and Carmeliet [2], in which three assessment methods were distinguished: measurements, semi-

---

[*] Corresponding author. Building Physics and Services, Eindhoven University of Technology, P.O.Box 513, 5600 MB Eindhoven, The Netherlands. Tel.: +31 (0)40 247 2138; fax: +31 (0)40 243 8595.
E-mail address: b.j.e.blocken@tue.nl (B. Blocken).

http://dx.doi.org/10.1016/j.buildenv.2014.11.006

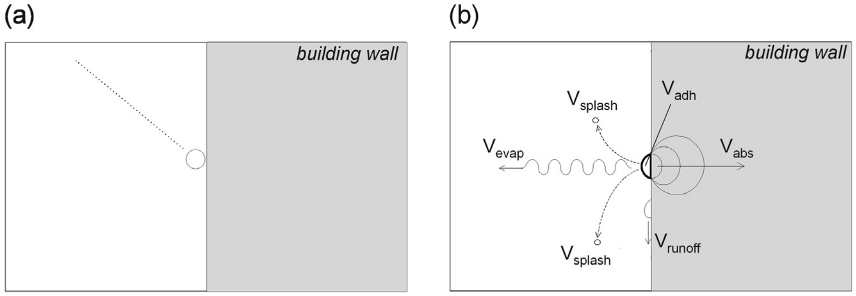

Fig. 1. Schematic representation of the two parts in wind-driven rain research: (a) assessment of the impinging wind-driven rain intensity (before rain impact) and (b) assessment of the response of the wall (at and after rain impact).

empirical formulae and numerical simulations based on Computational Fluid Dynamics (CFD). In the past 10 years, also more recent reviews on this first part of WDR research have been published [7–10]. Research on the first part of WDR is still fully ongoing, as evidenced by many recent publications in Building and Environment and other journals (e.g. Refs. [11–14]).

The second part in WDR research however has received much less attention. Although a very large number of studies focused on heat, air and moisture (HAM) transfer in building components, only relatively few of them focused in detail on WDR as a boundary condition (e.g. Refs. [15–22]). Abuku et al., in 2008 [17] focused on contact and surface phenomena such as spreading, splashing and bouncing on vertical building surfaces. Straube [18] extensively discussed rainwater penetration mechanisms including hydrostatic pressure, wind pressure, surface tension and gravity. Several authors performed studies of rainwater runoff on building facades [19–22]. An extensive review on rainwater runoff from building facades can be found in Ref. [23].

This paper presents an attempt to bridge the gap between the two parts in WDR research. It combines existing and new models for the study of the impingement and behaviour of raindrops on an impervious, smooth, vertical surface. In section 2, the CFD model used to calculate the WDR impingement is described. In section 3, the different sub-models of the droplet-behaviour model (including drop distribution, runoff and evaporation) are outlined. Section 4 presents the application of these models for a case study: WDR on a window glass surface in the facade of a two-storey building. Sections 5 (discussion) and section 6 (conclusions) conclude the paper.

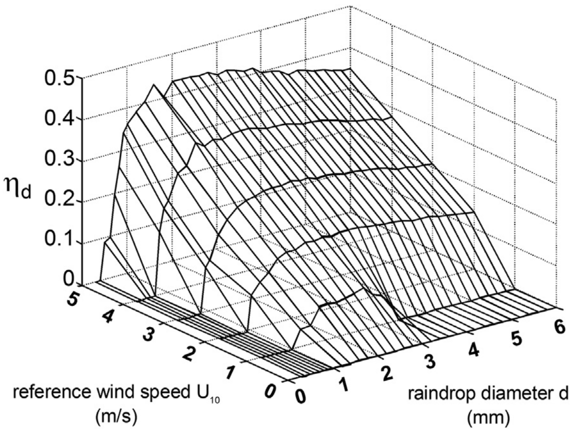

Fig. 2. Example of a specific catch ratio chart illustrating η_d as a function of the reference wind speed U_{10} (m/s) and the raindrop diameter d (mm) for a given wind direction and a given facade position.

2. CFD model for wind-driven rain impingement

2.1. Model description

The CFD model for WDR is based on the model by Choi [24] and on the extension and validation of this model by Blocken and Carmeliet [25,26]. This model can provide the spatial and temporal distribution of WDR on a building facade. Here, it is used to calculate the specific catch ratio for different positions at the building facade. For every raindrop diameter d, the specific catch ratio is defined as:

$$\eta_d = \frac{S_{wdr}(d)}{S_h(d)} \tag{1}$$

where $S_{wdr}(d)$ is the specific WDR amount on the building facade comprised of raindrops with diameter d (in L/m^2 or mm) and $S_h(d)$ is the specific horizontal rainfall amount comprised of raindrops with diameter d (i.e. unobstructed rainfall through a horizontal plane; in L/m^2 or mm). The procedure to obtain the specific catch ratio consists of three steps:

1. Simulation of the steady-state 3D wind-flow pattern around the building with the Reynolds-averaged Navier–Stokes (RANS) equations and the realizable k-ε turbulence model by Shih et al. [27].
2. Calculation of raindrop trajectories by injecting raindrops in the calculated wind-flow field and by solving their equations of motion by Lagrangian particle tracking. This is done for different values of the reference wind speed U_{10} (m/s at 10 m height), the wind direction φ_{10} (° from north) and for the entire range of raindrop diameters ($d = 0.3–6$ mm).
3. Determining the specific catch ratio for each raindrop diameter from the geometrical configuration of the raindrop trajectories.

The specific catch ratio is calculated for different positions on the building facade, for different values of the reference wind speed U_{10} and wind direction φ_{10}. It is typically presented in a set of charts, displaying η_d as a function of U_{10} and d for a given position and a given wind direction (Fig. 2).

2.2. Model validation

The CFD model has been validated on several occasions in the past. Because of the importance of validation and for completeness of the present paper, a selection of results from one of these earlier validation studies [26] is briefly reproduced here. This study was performed for the isolated low-rise VLIET test building at Leuven University in Flanders, Belgium (Fig. 3). South-west of the building, some low-rise agricultural construction and a row of trees were