Building and Environment 44 (2009) 1675–1690

Contents lists available at ScienceDirect

Building and Environment

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

Wind-driven rain on the facade of a monumental tower: Numerical simulation, full-scale validation and sensitivity analysis

P.M. Briggen, B. Blocken*, H.L. Schellen

Building Physics and Systems, Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, The Netherlands

ARTICLE INFO

Article history:
Received 9 July 2008
Received in revised form
6 November 2008
Accepted 9 November 2008

Keywords:
Driving rain
Experimental data
Field measurements
Raindrop trajectory
Numerical simulation
Hygrothermal modelling

ABSTRACT

Wind-driven rain (WDR) is one of the most important moisture sources that affect the hygrothermal performance and the durability of building facades. The facades of the Dutch monumental building St. Hubertus show severe deterioration caused by WDR. Assessment of the amount and intensity of WDR falling onto the facades is necessary as input for numerical heat-air-moisture (HAM) transfer models to analyse the causes of the moisture problems and the impact of remedial measures. In this study, a numerical simulation method based on Computational Fluid Dynamics (CFD) is used to predict the amount of WDR impinging on the south-west facade of the tower of the building. The paper focuses on the numerical simulation results, the validation of these results and their sensitivity to two parameters: the level of geometrical detailing of the computational building model and the upstream terrain aerodynamic roughness length. Validation is performed by comparison of the numerical results with a dataset obtained from on-site WDR measurements. It is shown that the CFD simulations provide fairly good predictions of the amount of WDR impinging on the south-west facade of the tower, except for the lower part. It is also shown that the local effects of geometrical facade details are significant and can yield differences in WDR exposure up to 40%, while their effect at other positions is negligible. Finally, the sensitivity of WDR simulations to the upstream aerodynamic roughness length is discussed.

1. Introduction

Building Physics aims at providing a healthy, comfortable and sustainable indoor and outdoor environment of buildings. Sustainability also involves the durability of the building envelope that separates the indoor and the outdoor environment. Wind-driven rain (WDR) is one of the most important moisture sources that affect the hygrothermal performance and the durability of building facades [1–5]. Numerical analysis of the hygrothermal behaviour with so-called HAM (heat-air-moisture) models requires accurate WDR data as boundary condition [1–8].

Three categories of methods exist for determining the WDR intensity that impinges on building facades: (1) measurements, (2) semi-empirical methods and (3) numerical methods based on Computational Fluid Dynamics (CFD). A literature review of each of these categories has been provided by Blocken and Carmeliet [5]. Measurements have always been the primary tool in WDR research, but are nowadays only rarely conducted. The most important reason is the fact that WDR measurements can easily suffer from large errors [3,9–11]. Recently, guidelines have been proposed that should be followed for selecting accurate and reliable WDR data from experimental WDR datasets [10,11]. The strict character of these guidelines, however, implies that only very few rain events in a WDR dataset are accurate and reliable and hence suitable for WDR studies. Other drawbacks of WDR measurements are the fact that they are time-consuming and the fact that measurements conducted at a particular building site have very limited application to other sites. Semi-empirical methods are an alternative to measurements. The main advantage of semi-empirical methods is their ease-of-use; their main disadvantage is that generally only rough estimates of the WDR exposure can be obtained [5]. Given the limitations of measurements and semi-empirical methods, in the past decades, numerical simulation with CFD has been explored. Choi [12–14] developed and applied a steady-state numerical simulation technique based on CFD. It allows determining the spatial distribution of WDR on building facades for given (fixed) values of the wind speed, the wind direction and the horizontal rainfall intensity. Later, Choi's simulation technique was extended into the time domain by Blocken and Carmeliet [15,16]. In all of these studies, CFD simulations were based on the Reynolds-Averaged-Navier–Stokes (RANS) equations.

Validation is an essential part of RANS CFD simulations. Up to now, only a few attempts have been made for CFD validation with full-scale WDR measurements [3,5,15,17–19]. van Mook [3] was the

* Corresponding author. Tel.: +31 (0)40 247 2138; fax: +31 (0)40 243 8595.
E-mail address: b.j.e.blocken@tue.nl (B. Blocken).

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doi:10.1016/j.buildenv.2008.11.003

Nomenclature

C_S	roughness constant (–)
d	raindrop diameter (mm)
E_{AW}	absolute adhesion-water-evaporation error (mm)
E_{RW}	absolute rest-water error (mm)
E_{wdr}	absolute WDR measurement error (mm)
e_{wdr}	relative WDR measurement error ($=E_{wdr}/S_{wdr}$) (–)
$f_h(d)$	probability-density function of raindrop size falling through a horizontal plane (m^{-1})
I_u	turbulence intensity (–)
k	turbulent kinetic energy (m^2/s^2)
k_s	physical roughness height (m)
L, B, H	length, width and height of the computational domain (m)
R_h	horizontal rainfall intensity, i.e. through a horizontal plane (L/m^2h of mm/h)
R_{wdr}	wind-driven rain intensity (L/m^2h of mm/h)
S_h	horizontal rainfall amount, i.e. through a horizontal plane (L/m^2 or mm)
S_{wdr}	wind-driven rain amount (L/m^2 or mm)
u^*_{ABL}	friction velocity associated with the inlet profiles of U, k and ε (m/s)
U, V, W	streamwise, vertical and lateral component of the mean wind-velocity vector (m/s)
U_{10}	reference wind speed at 10 m height in the upstream undisturbed flow (m/s)
$U(y)$	mean streamwise wind speed at height y (m) above the ground plane (m/s)
y	height co-ordinate (m)
y_0	aerodynamic roughness length (m)
y_P	distance from the centre point P of the wall-adjacent cell to the wall (m)
ε	turbulence dissipation rate (m^2/s^3)
η_d	specific catch ratio (–)
η	catch ratio (–)
κ	von Karman constant (≈ 0.42)
φ_{10}	reference wind direction at 10 m height in the upstream undisturbed flow (degrees from north)
ABL	Atmospheric Boundary Layer
CFD	Computational Fluid Dynamics
HAM	Heat-Air-Moisture
RANS	Reynolds-Averaged-Navier–Stokes (equations)
WDR	Wind-Driven Rain

first to compare simulations with full-scale measurements at a few selected positions at the west facade of a wide, high-rise building. Blocken and Carmeliet [15,18] performed CFD WDR validation for a low-rise building with a sloped and a flat roof module, based on measurements with 24 WDR gauges installed at the south-west and north-west facades. Tang and Davidson [17] validated numerical simulations for the rather complex Cathedral of Learning with WDR measurements at 16 different positions. Most recently, Abuku et al. [19] employed the WDR measurement data by Nore et al. [20] for the validation of WDR simulations on the west facade of a low-rise rectangular test building with various angles of wind incidence. While some authors found significant discrepancies between simulations and measurements [3], others indicated a fair to good agreement [15,17–19].

While these efforts have provided valuable information, the need for additional WDR measurement data and CFD validation studies is still present, in particular for different types of buildings in different environment topographies [11,18]. This need is driven by the complex nature of WDR and the wide range of influencing parameters. Additionally, sensitivity studies are needed concerning the large amount of computational parameters that have to be set by the user in such CFD simulations. Two important questions are: (1) to what extent do geometrical facade details have to be included in the computational model of the building; and (2) how sensitive are the results to the estimate of the aerodynamic roughness length of the upstream terrain. The inclusion of facade details can present a challenge in CFD WDR studies, due to the large difference in length scales between the computational domain (up to several 100 m or km) and the facade details (down to a few cm) and the subsequent need for very fine grids near the building surface. The aerodynamic roughness length determines the shape of the inlet profiles of mean wind speed, turbulent kinetic energy and turbulence dissipation rate, as well as the physical roughness height k_S that has to be applied at the bottom of the computational domain [21]. It is generally estimated from the updated Davenport roughness classification by Wieringa [22], based on a fetch (upstream distance) of at least 5 km (Table 1). However, estimating a representative aerodynamic roughness length for heterogeneous terrain is difficult, and it is therefore rather easy to be one class off in this roughness classification.

In this paper, CFD simulations of WDR on the south-west facade of the tower of Hunting Lodge St. Hubertus (Fig. 1a) are performed. It is a monumental building situated in the National Park "De Hoge Veluwe". Especially the south-west facade of the building shows severe deterioration caused by WDR and subsequent phenomena such as rain penetration, mould growth, frost damage, salt crystallisation and efflorescence, and cracking due to hygrothermal gradients (Fig. 1b–e). The CFD WDR simulations are important to obtain accurate spatial and temporal distribution records of WDR, to be used as input for numerical HAM transfer simulations. These simulations will be used in a later

Table 1
Davenport classification of aerodynamic terrain roughness length as updated by Wieringa [22]. Values can be extracted from the table by a visual determination of the roughness class on condition that it is based on a fetch of at least 5 km.

	y_0 (m)	Landscape description
1	0.0002 Sea	Open sea or lake (irrespective of the wave size), tidal flat, snow-covered flat plain, featureless desert, tarmac, concrete, with a free fetch of several kilometres.
2	0.005 Smooth	Featureless land surface without any noticeable obstacles and with negligible vegetation; e.g. beaches, pack ice without large ridges, morass, and snow-covered or fallow open country.
3	0.03 Open	Level country with low vegetation (e.g. grass) and isolated obstacles with separations of at least 50 obstacle heights; e.g. grazing land without windbreaks, heather, moor and tundra, runway area of airports.
4	0.10 Roughly open	Cultivated area with regular cover of low crops, or moderately open country with occasional obstacles (e.g. low hedges, single rows of trees, isolated farms) at relative horizontal distances of at least 20 obstacle heights.
5	0.25 Rough	Recently-developed "young" landscape with high crops or crops of varying height, and scattered obstacles (e.g. dense shelterbelts, vineyards) at relative distances of about 15 obstacle heights.
6	0.50 Very rough	"Old" cultivated landscape with many rather large obstacle groups (large farms, clumps of forest) separated by open spaces of about 10 obstacle heights. Also low large vegetation with small interspaces such as bush land, orchards, young densely-planted forest.
7	1.0 Closed	Landscape totally and quite regularly covered with similar-size large obstacles, with open spaces comparable to the obstacle heights; e.g. mature regular forests, homogeneous cities or villages.
8	$\geq$2.0 Chaotic	Centres of large towns with mixture of low-rise and high-rise buildings. Also irregular large forests with many clearings.