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Ten questions concerning modeling of wind-driven rain in the built environment

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ABSTRACT

Wind-driven rain (WDR) in the built environment is a complex multiscale phenomenon. Wind flows in complex urban environment and rain events of various intensities may lead to very different rain deposition distributions within the city. Proper modeling of WDR is required as moisture is a main cause of material degradation in the built environment but also as understanding the water cycle in the urban environment is essential to provide solutions for the urban heat island, amongst others. What are the main aspects to be taken into account to predict wind-driven rain? How should such aspects be considered and modeled? Is it possible and relevant to predict in detail the moisture loads due to rain in complex systems as cities? This paper answers these questions from a multiscale perspective combining modeling and experimental work. The different scales relevant for accurate estimation of wind-driven rain in the built environment are presented. Rain deposition on complex geometries can be modeled by CFD, taking into account turbulent dispersion. Such modeling provides the impact velocity and angle of attack for each droplet size at any location on the urban surfaces. Using this information and the structure of the surface, the fate of the rain droplets can be predicted, namely whether it splashes, bounces or simply spreads.

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1. Introduction

Rain in the built environment is a complex phenomenon which has impact on, amongst others, durability of the materials, vitality of urban vegetation, management of storm water and comfort, safety and health of the population. Not only does rain induce an environmental load on the surfaces it impacts, but, contrary to the other environmental loads of solar radiation and wind flow, a large part of the rain water remains present after the rain event and such presence must be accounted for despite the fleeting and stochastic nature of liquid flow. To properly capture rain, the different time scales of the phenomenon need to be considered. The first time scale is the few minutes rain droplets spend in the air before deposition. Air flow is drastically affected by the presence of buildings, influencing the distribution of rain load in the built environment. Then, the few milliseconds when droplets impact surfaces explain the different outcomes of spreading, splashing and/or rebound. The settlement of droplets on surfaces takes minutes, and the wetting of the surface and absorption in the porous media take several hours. In addition, as more and more droplets rest on a surface, they may coalesce and form a water film, resulting in rivulets and film run-off on the different surfaces. After a rain event, evaporation of the droplets and drying of the materials can take hours to days. As such rain deposition and the ensuing fate, i.e. the succession of subjected phenomena, of water is a multifaceted phenomenon which can be appropriately modeled at the different spatial and times scales due to recent computational advances.

A complete study of wind-driven rain (WDR) and the related moisture load on the urban environment takes into account WDR intensity as well as what happens after the impact of droplets. WDR is the type of rain, which is carried by wind and thus characterized by a horizontal velocity vector due to the effect of wind flow which affects the droplet trajectories. The horizontal component, R_{wdr}, of

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the oblique rain vector is the WDR intensity that causes a rain flux through a vertical plane, whereas the vertical component, R_h, is the rainfall intensity that causes a rain flux through a horizontal plane. WDR intensity is usually quantified with a catch ratio which normalizes the WDR intensity with the rainfall intensity:

$$\eta_d(d) = \frac{R_{wdr}(d)}{R_h(d)}, \quad \eta = \int_d f_h(R_h, d)\eta_d(d)\mathrm{d}d \tag{1}$$

where $\eta_d(d)$ denotes the specific catch ratio which is related to raindrop diameter d, η the catch ratio which is related to the entire spectrum of raindrop diameters, $f_h(R_h,d)$ the raindrop-size distribution through the horizontal plane. The distribution of catch ratios on building surfaces is influenced by building geometry, environment topography, position on the building facade, wind speed, wind direction, rainfall intensity and raindrop-size distribution [6,26]. The resulting droplet impact speed and impact angle, together with the surface and material properties of building facades, govern the fate of the droplets after impingement on the facade, especially for droplet spreading [50].

Different scales are involved in the distribution of WDR intensity within the built environment and the interaction of droplets with the built environment after impact. The principal features to be retained at these different scales and the relations between these features are discussed in this paper. The objective of this paper is to propose a global methodology to simulate rain entrained by wind within the built environment and to follow the fate of the deposited water. After a presentation of the physics and relevance of rain in Question 1, the methodology is presented through the answers of questions 2 to 8. The need for such methodology and its future applications are discussed in the last two questions.

2. Questions

Question 1: What is the relevance and significance of WDR in the built environment?

WDR is one of the most important surface wetting and moisture sources on building facades [7]. Deterioration of building structures due to moisture usually begins in the regions where WDR impingement is the highest. Raindrops that strike and are deposited on a building surface can be absorbed or can run off, both with potentially damaging consequences. As a result of absorption, rain water ingress is possible in case of an inadequate capillary break [66], in case of solid masonry, interior surface problems, such as mold growth, can arise due to moisture transported by capillary action [2,34] or in case of wood-framed walls, by solar-induced thermal gradients (Carmeliet and Derome [23]; Carmeliet and Derome [24]). As a result of run-off, water can leak into the building facade through cracks. Water in porous materials can lead to several undesired phenomena, such as frost damage on exterior wall surfaces [69], erosion of building materials [65], moisture-induced salt migration [25], discoloration by efflorescence [32] and surface soiling [29]. Moreover, the conservation of historic buildings, the design of new buildings and the development of new building materials rely on the correct prediction of moisture loads [21]. The correct prediction of WDR is also significant in the assessment of environmental risks related to the leaching of harmful biocides and nanoparticles from buildings [68]. WDR deposition in the built environment sees these mentioned effects propagating through different urban surfaces, including, in addition to building facades, roofs, vegetated areas and paved streets, pedestrian ways, etc.

The distribution of surface wetting in the built environment is related to the interaction of raindrops of different size with wind flow. An overview of various relationships describing raindrop-size distributions is given by Uijlenhoet and Stricker [67]. Fig. 1a shows the raindrop size distribution through a horizontal plane based on the raindrop size distribution in the air, e.g. by Best [5]. For lower rainfall intensities, the probability distribution curve has a sharp shape and raindrops are of smaller size. As the rainfall intensity increases, larger raindrops tend to get more frequent and the probability distribution curve gets broader. The smallest size droplets in the spectrum can easily follow the vortical structures in the air flow around and between the buildings and hit shielded building facades due to their small inertia, while larger droplets are less influenced by wind flow patterns due to their inertia. As a result, different surface wetting patterns can be obtained at different rainfall intensities, even in identical wind flow conditions. Fig. 1b and (c) show the catch ratio distributions on the windward facade of a cubic building for a reference wind speed of 10 m/s and for rainfall intensities of 1 mm/h and 30 mm/h. For both rainfall intensities, the highest values are observed at the top corners due to the higher wind speed at higher heights along with the acceleration of the wind flow around the edges of the building. However, for the higher rainfall intensity, thus events with larger droplets, the wetting gradient gets smaller, with lower maximum catch ratio and higher minimum catch ratio. The distribution of surface wetting influences the wetting and drying conditions in the built environment. In particular, WDR analysis is required for the evaluation of mitigation solutions, relying on evaporative cooling, for local and urban heat islands in the built environment. Also, WDR distribution via its impact on local environment and building surface conditions is related to energy consumption of buildings and urban systems.

Given the large relevance and significance of WDR in the built environment, in the past years, several reviews on the topic have been published [7], providing an extensive review of the history of wind-driven rain research, with specific focus on assessment methods such as on-site experiments, wind-tunnel experiments, semi-empirical formulae, WDR maps and numerical simulation based on Computational fluid dynamics (CFD). A later review by Blocken and Carmeliet [15] focused in detail on the evaluation of three calculations models for WDR based on the model theory: the semi-empirical model in the ISO Standard for WDR [37], the semi-empirical model by Straube and Burnett [62] and the CFD model by Choi [26]; extended by Blocken and Carmeliet [6]. This review highlighted the strengths and limitations of these models and their predictive capability, based on the extent to which the different influencing parameters of WDR are implemented in the models. More recent reviews can be found in [17,55] and [20].

Question 2: What are the most effective modes of investigation to properly capture WDR?

Determining the distribution of WDR intensity can be performed with three general methods: experimental, semi-empirical and numerical methods. Field measurements of WDR on building facades are difficult to set up and time-consuming as they are confined to the meteorological conditions present at the time of experiments. Moreover, they are prone to errors mainly due to the uncertainties in measurement environment and measuring instruments [8,10,35]. Semi-empirical methods are, on the other hand, fast and easy to use. However, they are defined for specific building configurations and mostly do not take into account all relevant factors [41]. shows that the deviations between semi-empirical models and field measurements can be up to 88%. Furthermore, various semi-empirical models can show differences of up to 300% [16,17,28,41]. Semi-empirical methods are generally

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