

Field measurements and numerical modelling of wind-driven rain: absorption and runoff on building materials

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SUMMARY

Wind-driven rain (WDR) significantly affects the hygrothermal performance and durability of exterior surfaces, yet runoff processes on porous materials remain poorly understood. This study presents detailed field measurements of WDR absorption and runoff on various stones and clay bricks using cube-shaped building models, with sensors recording water uptake and runoff alongside meteorological data. Porous samples of different thicknesses were analyzed, and one-dimensional numerical simulations were performed using standard coupled heat and moisture transport formulations. Results show that thinner samples quickly reach capillary saturation, while thicker ones often remain partially unsaturated, leading to lower runoff. Simulations tend to underestimate runoff, particularly for thicker materials, highlighting limitations of applying WDR as a simple surface flux. Factors such as droplet impact dynamics, surface wetness, and early evaporation contribute to discrepancies. To address this, a WDR Reduction Factor is proposed, applying a penalty based on surface capillary pressure to better represent runoff initiation in numerical models.

Keywords: Wind driven rain, runoff, absorption, high-rise buildings

1. INTRODUCTION

Wind-driven rain (WDR) plays a major role in the hygrothermal behavior and long-term durability of exterior surfaces. For this reason, WDR intensity is commonly used as a boundary condition in moisture-transport analyses of building envelopes. The amount of WDR reaching urban surfaces can be estimated by numerically modeling airflow around buildings together with the motion of raindrops (Kubilay et al. 2013). After droplets hit a surface, they may undergo a range of complex processes, such as spreading, splashing, rolling or rebounding, coalescing, surface wicking, absorption into porous materials, evaporation, film formation, and gravitational runoff. Although previous research has addressed absorption and moisture transport, film development and runoff on building materials have received comparatively little attention (Martin et al. 2015) and only limited experimental or numerical runoff data are currently available (Derome et al. 2017). Reliable development and validation of numerical models therefore require comprehensive measurement datasets.

To support this need, the present study provides detailed field measurements of WDR absorption and runoff on porous building materials. The objective of the study is to determine the moisture uptake of these materials and to identify the onset and extent of runoff. Measurements are compared with one-dimensional numerical simulations.

2. CASE STUDY AND METHODOLOGY

Field measurements were carried out from April to November 2019 using two parallel cube-shaped building models ($2 \times 2 \times 2$ m), as shown in Fig. 1. Earlier campaigns used a similar setup to determine WDR distributions on the facades (Kubilay et al. 2015). In this study, porous materials with different pore structures, absorption properties, and thicknesses are added alongside the WDR gauges. Figure 1a shows the sensor layout, and Fig. 1b displays two Savonnières limestone samples at location C. Porous materials are installed at locations A, B, and C on the downstream cube of varying types (Pietra Serena sandstone, Meule sandstone, Savonnières limestone, and clay brick) and thicknesses (8 and 20 mm), allowing comparison of how material properties influence absorption and runoff. Each of the ten collectors has a load cell for measuring the amount of water absorbed, and runoff is recorded via a tipping-bucket system connected through internal tubing. A WDR gauge is installed at each location, with additional ones on the upstream cube. A meteorological mast west of the setup measures approach wind using a 3D ultrasonic anemometer and two cup anemometers. A rain gauge 0.4 m above ground records horizontal rainfall intensity, while humidity, air temperature, and solar radiation are also monitored to fully document rain events.

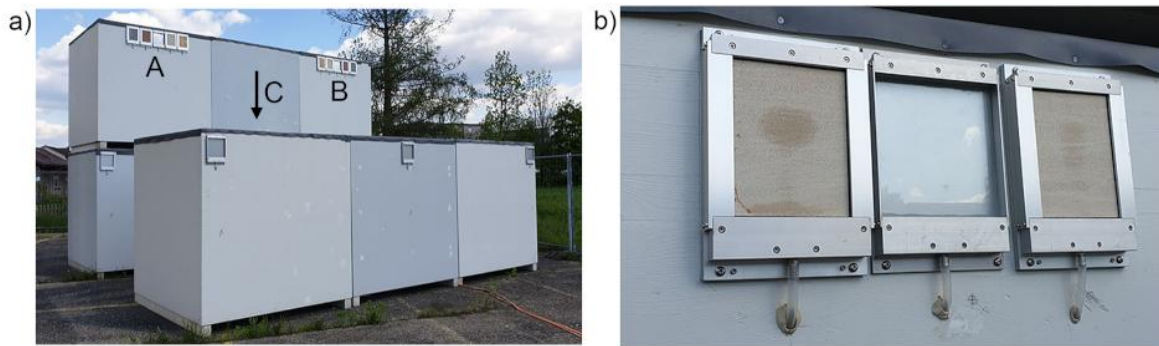


Figure 1 (a) Global view of experimental setups, with 9 cubes. (b) Close-up of rain gauges, left Savonnières 8mm, mounted to measure run-off and absorption, center, regular rain gauge, (right) 20 mm thick Savonnière sample

In this study, the porous material samples (20×15 cm²) are modeled using one-dimensional numerical domains. The hygrothermal behavior is solved using a standard coupled heat and moisture (HAM) transport formulation (Janssen et al. 2007). Heat transport includes conductive and convective heat transfer also considering latent heat effects. Heat is stored according to the heat capacity of the wet material. Convective heat exchange at the surface is represented through an external heat-transfer coefficient depending on wind speed.

Moisture transport includes liquid water and water vapor transport. The moisture capacity is described by the capillary pressure curve representing the relation between moisture content and capillary pressure. At the surface, moisture exchange includes not only the incoming rain flux but also evaporation represented by a surface moisture transfer coefficient.

Rainwater is absorbed by capillary suction until capillary moisture content is reached. When the surface is capillary saturated incoming rain is no longer taken up by the material but instead flows

down the surface as runoff, which is not explicitly modelled but excess water is removed from the simulation as runoff.

The open-source 3D HAM code referred to as *hamFoam* (hamFoam 2025) and developed by the authors is used, which uses the control volume technique to solve the heat and moisture balance equations. The model has been validated using the HAMSTAD benchmark studies, ensuring that it meets high standards of accuracy (Ferrari et al. 2020). *hamFoam* may operate in three dimensions, and uses an adaptive time step, which improves efficiency and accuracy, especially in transient simulations where conditions change rapidly.

3. RESULTS

Figure 2 presents a multi-spell rain event recorded between 9 and 16 June 2019, showing the absorption and runoff measured on the two Savonnières limestone samples at location C, together with the total WDR collected by the reference gauge. The data indicate that the 8-mm specimen reaches capillary saturation during all three rain spells, whereas the thicker 20-mm sample does not fully saturate during the first two spells, leading to noticeably lower runoff. In the numerical simulations, the total measured WDR is applied as a surface rain-flux boundary condition. Comparison with the experimental results reveals that the model consistently underpredicts runoff for both sample thicknesses. For the 8-mm material (Figure 2a), the simulation reproduces the absorbed water and subsequent evaporation reasonably well. However, for the 20-mm sample (Figure 2b), the model overestimates absorption during the first two spells. Although the simulation approaches saturation during the initial rainfall period, it still produces much less runoff than observed. This discrepancy highlights the limitations of applying a simple flux boundary condition for WDR on façades, as it does not represent the behavior of individual raindrops after impact. Since droplet spreading, coalescence, and film formation differ markedly between dry and already wet surfaces, numerical models must incorporate these surface-scale processes in order to more accurately represent moisture transport during rainfall.

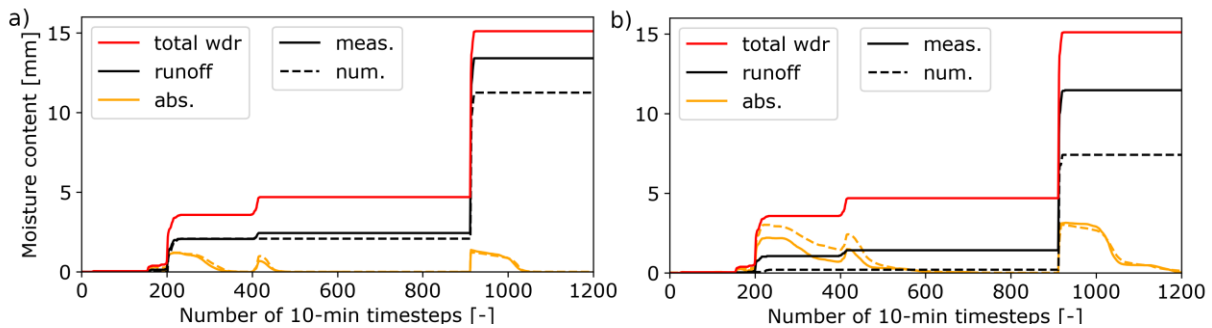


Figure 2. Comparison of the experimental absorption and runoff amounts with the numerical results on the a) 8-mm and b) 20-mm Savonnières stone samples..

While the applied boundary condition effectively triggers runoff once the surface reaches saturation, in reality, runoff may start before the surface is capillary saturated. Several factors could explain this discrepancy. Individual droplets impacting the surface may begin to run off before being absorbed due to oblique impact angles, changes in surface tension when the surface is wet compared to dry, gravitational effects, or the arrival of successive droplets at the same location

before the previous droplet has been absorbed. In addition, discrete droplets may start evaporating before absorption is complete. Considering these mechanisms it is essential for improving the accuracy of the model, and incorporating a dynamic contact angle or surface-specific penalty could provide a better representation of runoff initiation under real-world conditions. Therefore, we developed a new method introducing a WDR Reduction Factor, which applies a penalty to the WDR load, dependent on the capillary pressure at the surface accounting for the wetness of the surface in a simple way. This new method will be explained in detail and exemplified at the conference.

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