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Wind-driven rain and runoff on a medium-rise building: experimental and numerical analysis

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SUMMARY:
As wind-driven rain (WDR) is one of the most important moisture sources for a building envelope, a reliable prediction of the WDR and runoff load is a prerequisite to assess the durability of building facade components. Current state-of-the-art Heat Air and Moisture (HAM) models neglect the influence of runoff.

This study contributes to research efforts to develop models that combine state-of-the-art HAM models with a runoff model. It incorporates excess water that is present at the surface of the material in the form of a runoff layer. Available models for runoff on porous materials are however insufficiently validated. Therefore the experimental part of the present study focuses on collecting a dataset containing WDR intensities and corresponding runoff flow rates on the southwest facade of a medium-rise building.

For this experimental analysis, four modules with known cladding material with incorporated WDR and runoff gauges were mounted on the facade. These gauges are linked to pressure sensors measuring the supplied WDR and runoff every 10 seconds. The dataset is supplemented with detailed meteorological measurements. In this paper, we present the full scale experimental setup and its accuracy, the results of a first measurement campaign and a comparison between measurements and numerical results of a runoff model for a single rain event. From this comparison guidelines for future development of runoff models are deduced.

1. Introduction

Wind-driven rain (WDR) is a significant moisture source for building facades. It affects the hygrothermal behaviour and durability of the building materials and the aesthetic performance of the facade. The interaction of WDR with the building facade is rather complex and is dependent on a large set of urban, building, material and meteorological parameters (Blocken et al. 2013). Distribution of moisture in walls composed of porous building materials has been extensively studied in the past and this aspect can be modelled quite adequately. Splashing, bouncing, spreading and adhesion of raindrops on facades was previously investigated by Abuku et al. (2009). Research on film forming, runoff and film absorption is however limited. Most research on runoff and surface soiling is based on field observations (e.g. Küntz & van Mier 1997; Etyemezian et al. 1998; Etyemezian 2000; Davidson et al. 2000) while numerical work is limited to a few attempts (Blocken & Carmeliet 2012; Van den Brande et al. 2013).

Runoff contributes to surface soiling, both dirty and white washing of facades (Küntz & van Mier 1997; Davidson et al. 2000; Etyemezian 2000), rain infiltration due to preferential runoff paths (Hens 2010) and leaching of nanoparticles into the environment (Kaegi et al. 2008; Kaegi et al. 2010). Kaegi et al. (2010) clearly related leaching to the runoff that occurred at the walls surface. It is therefore important to get a clear idea of the runoff rate present on the outer facade.

1.1 Experimental measurements of runoff

Previous experimental research towards quantifying runoff rates is, to the authors' knowledge, mainly limited to the work of Beijer & Johansson (1977). They investigated the surface flows on a concrete facade and the ability of these flows to clean the facade. The experiment consisted of combined WDR and runoff measurements at four heights along the facade combined with horizontal rainfall measurements. Due to the limited knowledge of the used building materials and lack of detail in the published measurements it is only possible to estimate the total amount of runoff during a rain event. Beijer & Johansson also pointed out that due to the design of the WDR and especially the runoff gauges, measurement errors were introduced. Blocken & Carmeliet (2006) state that the error on WDR measurements can be very large (up to 100%) and that these errors depend on the type of rain event and on the design of the gauge. They concluded, following Högberg et al. (1999), that a polymethyl-methacrylate (PMMA) finish of the gauge is to be preferred over a polytetra-fluoroethylene (PTFE) finish, a small collection area is preferable to limit adhesion-water-evaporation, the drainage tube from the gauge to the reservoir should be as short as possible, and the height of the rim of the WDR gauge should be limited to reduce wind induced errors.

1.2 Modelling of runoff

The obtained measurements of the runoff flow will be compared with the predicted flow by the lubrification equation (Greenspan 1978; Ruyer-Quil & Manneville 1998). To the authors' knowledge, the only numerical model that has been applied for runoff on facades, is a simplified form of the lubrification equation (Blocken & Carmeliet 2012, Van den Brande et al. 2013). In Van den Brande et al. (2013), a state-of-the-art Heat, Air and Moisture (HAM) model was extended with a module to calculate the runoff of rainwater on the exterior surface of the building envelope. This model takes non-uniform WDR distributions into account as a boundary condition, using catch ratio distributions, and simulates the dynamic distribution of moisture in the wall. The model was then applied to a theoretical example of a low-absorbing building facade under a given WDR load and with constant convective moisture transfer coefficients (CMTC).

In the present paper, the measured WDR and micrometeorological conditions will be used as input and boundary conditions for the model. The thickness of the runoff layer for a non capillary active facade can be described by:

$$\frac{\partial h}{\partial t} + \frac{\rho g}{3\mu}\frac{\partial h^3}{\partial x} = \frac{q_{WDR} - q_{evap}}{\rho} \tag{1}$$

Where
- h the thickness of the runoff layer (m)
- ρ the density of water (kg/m³)
- g the gravitational acceleration, 9.81 m/s²
- μ the dynamic viscosity of water, in function of the temperature (kg/(m s))
- x the vertical coordinate along the wall
- q the supplied (subscript *WDR*) or evaporated (subscript *evap*) moisture flow (kg/(m²s))

the amount of evaporated water in Eq. 1 can be obtained by Eq. 2. If there is no runoff layer present, no evaporation is possible. When a runoff layer is present, a fully saturated surface is assumed.

$$q_{evap} = CMTC \cdot \left(p_{v,surf} - p_{v,air}\right) \tag{2}$$

Where
- CMTC the convective moisture transfer coefficient (s/m)
- $p_{v,surf}$ the vapour pressure at the surface of the wall (Pa)
- $p_{v,air}$ the vapour pressure of the outside air (Pa)

The CMTC used in Eq. 2 is based on empirical relations for the convective heat transfer coefficient (CHTC) and the Lewis analogy (Janssen et al. 2007) between the CHTC and the CMTC. The relation for the CHTC at the sixth floor of a windward facade derived by Sharples (1984) is used for the simulations in this paper:

$$CHTC = 0.5 \cdot W_s + 3.8 \qquad (3)$$

Where W_s the reference wind speed at 10 m above the ground (m/s)

More details on the model and its assumptions can be found in (Van den Brande et al. 2013). Runoff however is a complex phenomenon and is dependent on many more parameters as included in this model. For example, surface roughness, near-wall wind speed, adhesion forces of the liquid layer and droplet impact may also influence the behaviour of the runoff layer.

2. Description of the experimental setup

During the late summer – early fall (August 2013 – November 2013) WDR and runoff measurements were conducted on the southwest facade of the medium-rise S.E.G. building, located in Heverlee, Belgium (FIG. 1). An external facade with embedded WDR gauges and runoff gauges was developed, allowing an accurate positioning of the gauges and the possibility to change the finishing material in later experiments. The building has a height of 22 m. Four modules, each consisting of a flat, non capillary active, facade finishing board of 0.6 m by 2.4 m, and each containing a WDR gauge and a runoff gauge were mounted on the top-right corner of the south-west facade, 0.7 m from the side and 0.15 m from the top.

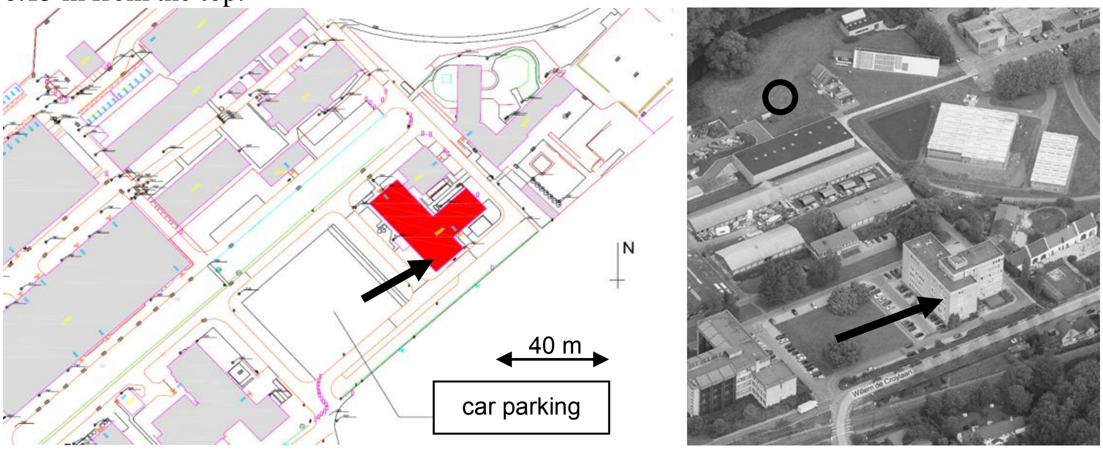

FIG 1. Surroundings of the S.E.G. building, located at the Leuven University Campus in Heverlee, Belgium. The position of the modules is depicted with an arrow, the location of the VLIET weather station is depicted with a circle in the aerial photograph.

In FIG. 2., the positions and dimensions of the WDR gauges and runoff gauges are depicted. The gauges are made of PMMA. The WDR gauges have a collection area of 0.2 by 0.2 m², while the runoff gauges measure runoff along a horizontal line of 0.2 m. The WDR gauge is placed recessed in the plane of the panel. A detailed description of the WDR gauge and its potential measurement errors can be found in (Blocken & Carmeliet 2006; Abuku et al. 2009). The newly developed runoff gauges include a thin slit with rounded edges in the plate material, thus making it possible for the runoff water to flow to the back of the panel where it is collected in a PVC reservoir (FIG. 2., bottom right).

Each of the WDR gauges and runoff gauges is connected to a PVC reservoir with diameter 30 mm by a short PVC tube. The height of the water column in this reservoir is measured every 10 s with a pressure sensor (type PTX 1400). Following the guidelines derived in (Blocken & Carmeliet 2006) by limiting the tubing length, using PMMA and PVC for the gauges, collectors and tubing and limiting evaporation losses, the measurement error of the runoff sensor can be described by the measurement error on the pressure sensors that monitor the water column, which is equal to 0.15 % of the measured value and a resolution of 2.10^{-4} kg and a small amount of adhesion water in the tubing. For the WDR gauges, an additional absolute error of 0.10 ± 0.02 kg/m² as a result of adhesion water can be considered (Blocken & Carmeliet, 2006).

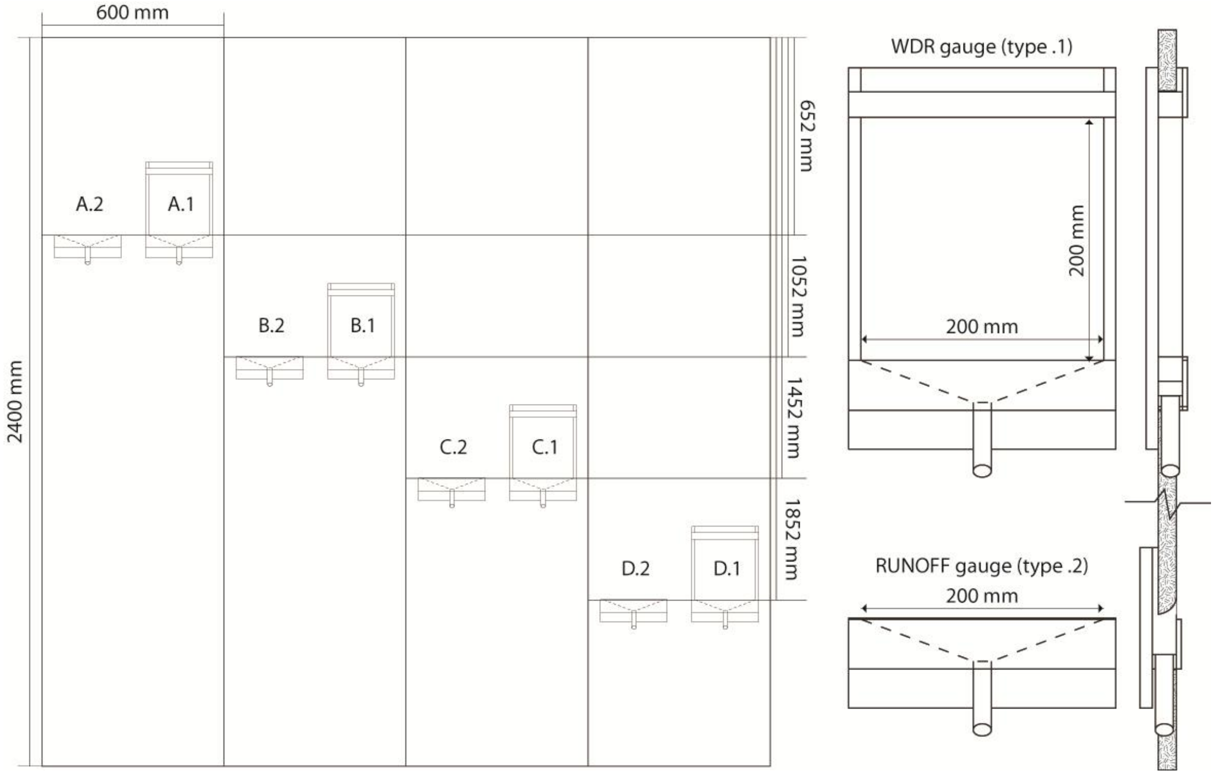

FIG 2. Position, dimensions and numbering of the WDR gauges and runoff gauges. Panels are named A to D, with A the panel the furthest from the top-right corner of the S.E.G. building. WDR gauges are assigned the number .1, runoff gauges the number .2. On the right-hand side of the figure two section views are shown, depicting a side view of the panel with incorporated gauges.

3. Results

A first comparison between measured and simulated runoff rates is made for a particular rain event that occurred on October 23th, 2013 from 16h50 until 17u10 during which a total amount of 2.7 mm horizontal rainfall was measured, which corresponds to a heavy shower. In this paper, only the results of panel C will be discussed. The micrometeorological conditions during this event are summarised in TABLE 1. In the model, the amount of WDR is considered constant over the height of the panel, however a small increase towards the top of the panel is expected.

For the particular shower, the model overestimates the amount of runoff by a factor 2.5 (FIG. 3). Both the flow rate, depicted by the slope of the curve and the total amount of runoff, depicted by the total height, do not correspond to the measured values. In the model, almost all supplied WDR is converted into runoff and the amount of retained water at the surface is limited. In the experiment however, a large amount of WDR does not run off, especially in the second part of the shower when low WDR loads are present.

This difference can be the result of neglecting surface adhesion of water in the runoff model. From experiments, it was found that the total amount of adhesion water on this specific panel can be up to 0.1 kg/m². The difference between measurements and the model can also find its origin in uncertainties on the dynamic viscosity of water, the assumptions made in the runoff model or the simplification of evaporation by the CMTC. Abuku (2009) also attributes the overestimation of the supplied WDR to the averaging error due to surface averaging the mass of individual droplets and to the error by neglecting splashing and bouncing of the impinging droplets.

In order to determine the origin of the difference between the measured values and the predicted values, a parameter study on a single measurement is performed. The results of this study are summarised in FIG. 4.

TABLE 1. Micrometeorological boundary conditions (wind speed W_s, wind direction W_{dir}, outdoor relative humidity RH an outdoor temperature T) and measured WDR rates Q_{wdr} (sensor C.1) and runoff rates Q_{runoff} (sensor C.2.)

Time from start	Q_{wdr} [kg/(m² s)]	W_s [m/s]	W_{dir} [°N]	RH [%]	T [°C]	Q_{runoff} [kg/(m s)]
0 - 4 min	0	4.31	257	89.9	14.37	0
4 - 8 min	$5.335 .10^{-3}$	3.66	227	89.9	14.37	$4.005 .10^{-3}$
8 - 12 min	$1.035 .10^{-3}$	2.68	235	93.6	14.37	$0.139 .10^{-3}$
12- 16 min	$0.368 .10^{-3}$	3.31	228	93.6	14.37	0
16 - 20 min	$0.138 .10^{-3}$	2.99	223	93.6	14.37	0

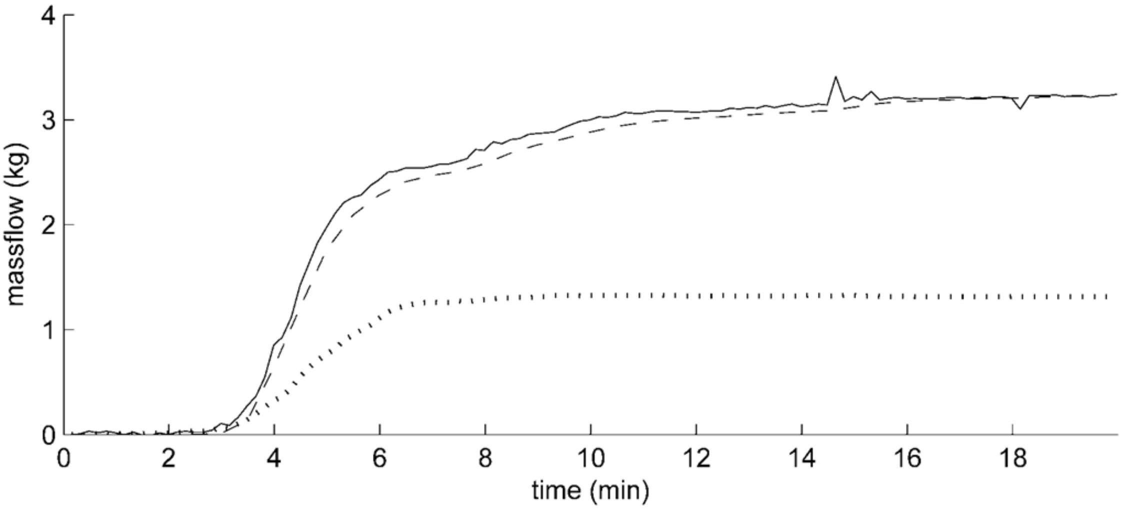

FIG 3. Modelled runoff rate (dashed line) compared to the measured runoff rate (dotted line) for a single shower rain event. The supplied WDR is depicted with a full line.

3.1 Effect of dust particles on the dynamic shear viscosity

The dynamic viscosity determines the flow rate described by the second term in Eq. 1. Higher viscosities result in smaller flows and thus more retained water. In this paper, an empirical relation between viscosity and temperature proposed by Kestin et al. (1978) is used for which is stated that the uncertainty on the absolute viscosity does not exceed 0.1% for a temperature range between -8 °C and 40°C. The uncertainty on the dynamic viscosity can therefore be attributed almost completely to the increase in viscosity as a result of dust particles. Following Einstein (1906) in his definition of the viscosity of slurry, one can say that the uncertainty on the dynamic viscosity is limited to a factor ±1.25, even if the amount of dust particles is high:

$$\mu_s = (1 + 2.5\phi_s)\mu_l \tag{3}$$

Where μ_s the dynamic viscosity of the slurry (kg/(m s))
μ_l the dynamic viscosity of the liquid (kg/(m s))
ϕ_s the volume fraction of the dust particles (-)

As seen in FIG. 4.a the effect of the increased viscosity is limited. At the start of the shower a small extra mass will be held in the runoff layer. Towards the end of the drying period, this mass will also run down the facade, thus barely changing the total amount of runoff. The increased viscosity decreases the runoff rate slightly but cannot account for the difference between the measurements and the model.

3.2 Effect of the uncertainty on the convective moisture transfer coefficients

Moisture transfer from the wall to the outer environment is dominated by forced convection due to wind. Therefore it depends on the local wind speed close to the wall, the pore structure and roughness of the surface, the moisture content at the surface and the local humidity. Determining local wind speeds around the experimental setup is an extensive task and reliable and fast models to determine case specific CMTC are lacking (Janssen et al. 2007). Due to these reasons, a simplified empirical relation between reference wind speed and a case independent CMTC is used (Eq. 3), in which the CMTC does not depend on building geometry, environment topography and surface properties of the material. Given the conclusions of Janssen et al. (2007), one can say that the error on the CMTC can go up to a factor 5.

In FIG. 4b. the results of a simulation with an increased CMTC are depicted with a blue dashed line. Due to the high humidity outdoors during the rain shower (see Table 1.) the evaporation rates are limited. The effect of the increased CMTC is only visible during the drying period, limiting the runoff rate, but cannot account for the difference between the measurements and the model.

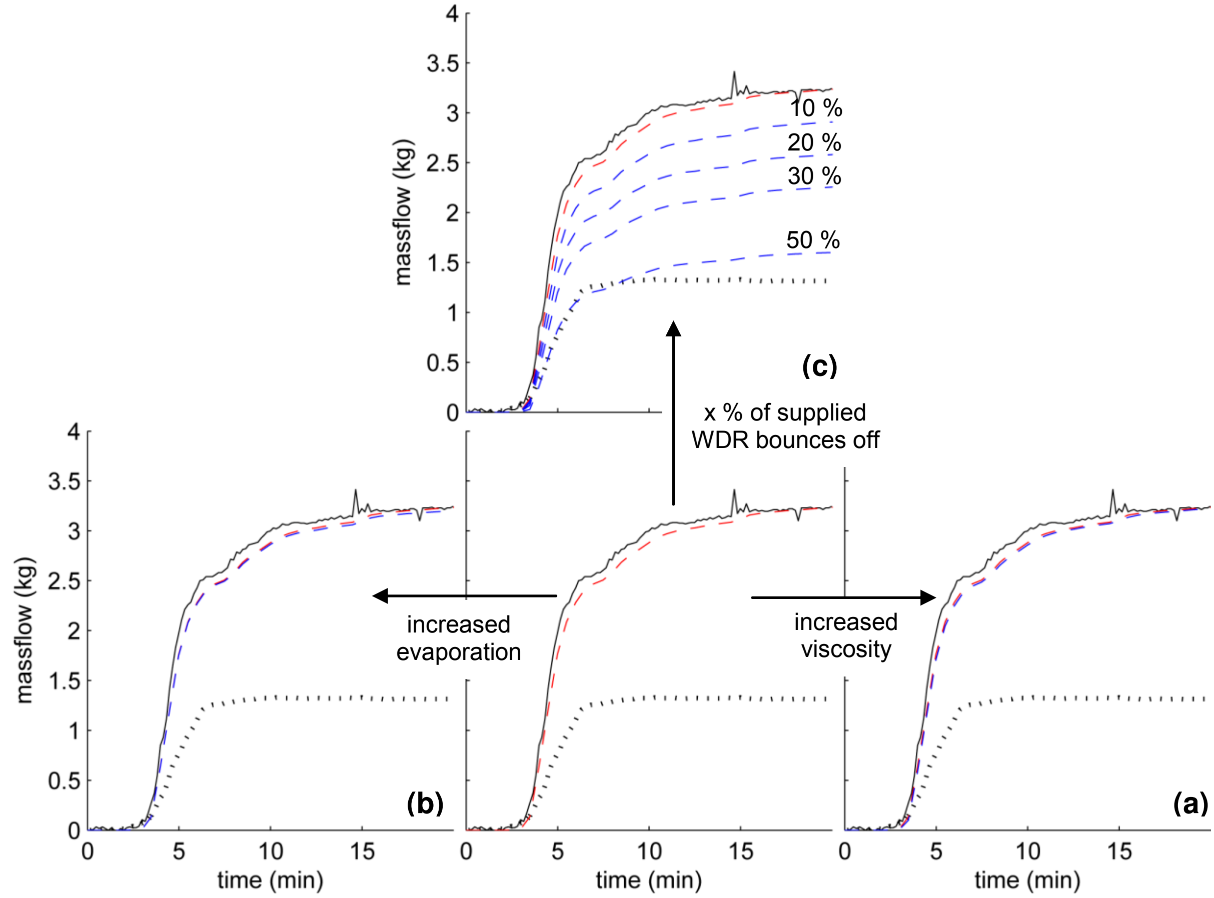

FIG 4. Results of the parameter analysis on the runoff model compared to the measured runoff rate. The measured runoff rate is depicted with a black dotted line, the measured supplied WDR with a full back line. The results of the model described by Van den Brande et al. (2013) are depicted with a red dashed line (equal in all figures), the results of the adjusted models with a blue dashed line.

3.3 Effect of bouncing and splashing of droplets

Due to splashing and bouncing of rain droplets part of the WDR flux is lost and does not contribute to the development of the runoff layer. The impact speed and impact angle of the individual raindrops and surface properties determine if a droplet splashes, bounces or spreads (Abuku et al. 2009). The impact of a droplet on a liquid film is even more unknown. These properties are tedious to measure and it is therefore difficult to correctly quantify the amount of water that actually contributes to runoff. In most WDR simulations, the impact speed and angle of different droplets are not reported making it also difficult to quantify the contribution of bouncing and splashing from simulations.

In FIG. 4c. the effects of the uncertainty on the supplied WDR are depicted. In each simulation a fraction of the supplied WDR is considered to bounce or splash, thus decreasing the supplied WDR. The figure shows that the effect of the uncertainty on the supply determines the result of the model. It is also visible there is also another factor that influences runoff that cannot be described by the model. During the second part of the event no runoff is measured whereas the model predicts a runoff flow due to the small amount of supplied WDR. This difference is in the same order of magnitude as the experimentally determined amount of adhesion water, namely 0.145 kg for the full panel.

4. Conclusions

In this paper the model proposed by Van den Brande et al. (2013) was compared with full scale runoff measurements on a medium-rise building. Measured WDR intensities and detailed micro-meteorological weather measurements were used as boundary conditions for the model. From the first comparison it was found that the model overestimates both the amount of runoff and the actual runoff rate. It was also found that it is necessary to model the adhesion water that is left after the runoff film flows down and to include bouncing and splashing of droplets. The uncertainty on the CMTC and the dynamic shear viscosity are found to be of less importance.

These results points out that future development in the model lies in a more precise experimental and numerical determination of the WDR intensities, including the effects after impact. Reports of WDR simulations should include, next to the moisture fluxes, also impact speed and angles making it possible to estimate splashing and bouncing. The current applied runoff model by Blocken & Carmeliet (2012) and Van den Brande et al. (2013) can also be improved by including surface adhesion of water.

5. Acknowledgements

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