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BIONICS AND WIND-DRIVEN RAIN ON BUILDING FACADES

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ABSTRACT

Rain penetration is one of the most important building facade defects. Rain penetration is usually not caused by the impact of direct wind-driven rain (WDR), but as its secondary effect, i.e., by rain run-off and accumulation of run-off at particular positions on a facade.
The aim of this paper is to predict the behavior of rain water on window surfaces and investigate the self-protecting effects of buildings. Two models are combined: a numerical model (CFD) for the direct WDR impact and a semi-empirical run-off model. The CFD model comprises the calculation of the wind-flow pattern, the resulting raindrop trajectories and the catch ratio as a measure of the amount of WDR falling onto certain parts of the facade. It permitss determining the intensity of direct WDR falling on a building façade, and it has been validated in earlier studies at the Laboratory of Building Physics, K.U.Leuven.

KEY WORDS

- *numerical simulation method*
- *semi-empirical method*
- *boundary condition*
- *raindrop trajectories*
- *catch ratios*

1 INTRODUCTION

1.1 Bionics and building environment

While studying the properties of building envelopes (e.g., wall and roof claddings) under loading from climate conditions, we can investigate and analyze a similar organism's behaviour in nature. Surface-covering tissues of plants, which create an "envelope structure", perform often opposing tasks. On one hand, the tissues protect the organisms from high and low temperature effects by increasing the thickness of the covering tissue. On the other hand, the extension of a tissue's thickness up to a certain level can be the result of the complete organism's isolation from the environment and the exclusion of the regulation of physiological treatment.

In terms of macrostructure, complicated envelope forms are created in nature to increase resistance of organisms in unfavourable conditions (wind, rain) on the basis of their shape (i.e., not by an extension of their material volume.) The processing technology permits the production of complex forms in a simple way. There are very interesting aerodynamic structural forms particularly resistant to wind blasts.
In term of microstructure the research has been done on the roughness of surfaces. The water resistant (e.g. , non-absorbing) properties of leaves has been recognized for a long time and well explored. However, it has not been observed that non – absorbing areas of rough leaf surfaces are difficult to be polluted as well.

1.2 Wind-driven rain

Wind-driven rain (WDR) on building facades belongs among the

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most important moisture source, affecting the general hygrothermal performance of wall claddings, and the amount of WDR is also one of the essential boundary conditions for Heat-Air-Moisture (HAM) transfer analysis. (Sanders, C., 1996, Van Mook, F. J. R., 2002, Högberg, A., 2002, Janssens, H. *et al*., 2008)
At the present time, there are three basic methods for determining the quantity of WDR: (1) measurements, performed using WDR gauges, (2) the semi-empirical method, which is using semi-empirical formulae to determine the quantity or intensity of WDR, and (3) the numerical simulation method, based on Computational Fluid Dynamics (CFD). (Blocken, B., and Carmeliet, J., 2004)
In our research, the last mentioned method was used to obtain the data for the calculation of rain water run-off along window surfaces and its accumulation at the window-wall interface.

1.3 Brief description of the calculation method used in our research

In order to calculate the total amount of rain water run-off, two models are combined: A numerical model (CFD) for the direct WDR impact and a semi-empirical rain water run-off model.

1.3.1 Numerical simulation method based on CFD

In order to calculate the spatial and temporal distribution of WDR on building facades using a numerical CFD model, the following steps are required. (Blocken, 2002):

1. A steady-state 3D wind-flow simulation around the building, using Reynolds-Averaged Navier-Stokes (RANS) equation and k-ε turbulence model.
2. Calculation of raindrop trajectories for 17 raindrop diameters and 8 windspeeds, based on raindrop injections in the calculated wind-flow pattern and solving their motion equations.
3. A specific catch ratio calculation for the given wind and raindrop pattern (as defined in 2.1)
4. The global catch ratio is calculated from the specific catch ratio charts which are reconstructed for different positions on the building facade, while using the raindrop size distribution $f_h(d)$ [m^{-1}] according to Best (1950)
5. In order to determinate the corresponding spatial and temporal distribution of WDR, the meteorological data record of the reference wind speed, wind direction and horizontal rainfall intensity for a given rain event with the appropriate catch ratios are used.

1.4 Description of the case study model

The reference model is a family house with a small garage,

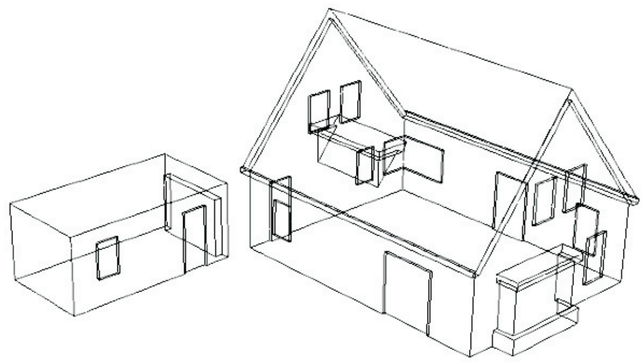

Figure 1. *Case study: 3D model of family house with garage.*

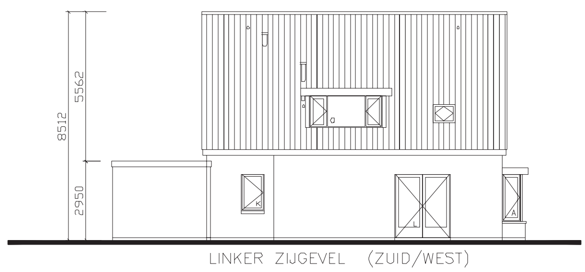

Figure 2. *View of the reference south west facade*

(Figure 1) built in Belgium. The main building is 10.9 m long and 8.15 m wide. The total height of the house with a sloped roof is 8.5 m; the garage height is 3 m.
In Belgium, the direction of the prevailing winds is south-west. Therefore, a longitudinal façade, deviating only 15˚ from the exact south-west orientation, was chosen. The reference facade has a height of 3 m and contains 2 windows of different sizes. Both windows are embedded 10 cm in the wall. The sloped-roof overhang depth is 30 cm.
The reference experimental house is built only recently, so the simulation data will be compared with measurements in the future.

2 DEFINITIONS OF VARIABLES AND DESCRIPTION OF THE CALCULATION METHODS

2.1 Specific and global catch ratio

A catch ratio in general means the ratio between the amount of rainfall intensity on the vertical surface of a building facade and the

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unobstructed horizontal rainfall is intensity.
A specific catch ratio is defined as:

$$\eta_d(d)=\frac{R_{wdr}(d)}{R_h(d)}\ [-]\ \text{or}\ \eta_d(d)=\frac{S_{wdr}(d)}{S_h(d)}\ [-]$$

where $R_{wdr}(d)$ [mm/h] and $R_h(d)$ [mm/h] are the specific WDR intensity and the specific horizontal rainfall for raindrops with diameter d [mm]. $S_{wdr}(d)$ and $S_h(d)$ = specific WDR sum (driven rain amount) and the specific horizontal rainfall sum (unobstructed horizontal rainfall amount).

A global catch ratio is defined as:

$$\eta_d(d)=\frac{R_{wdr}}{R_h}\ [-]\ \text{or by:}\ \eta_d(d)=\frac{S_{wdr}}{S_h}\ [-]$$

where R_{wdr} [mm/h] and R_h [mm/h] are the WDR intensity and horizontal rainfall integrated over all raindrop diameters. S_{wdr} and S_h are the WDR total and the horizontal rainfall total integrated over all the raindrop diameters.

2.2 Raindrop size distribution

The empirical formulae, which contains basic information about raindrop distribution, was formulated by Best (1950):

$$F(d)=1-\exp\left(-\left(\frac{d}{a}\right)^n\right)\ ;\ \text{where}\ a = A\ .\ (R_h)^p$$

F(d) is defined as the fraction of water in the air with a raindrop diameter less than d, and *A, n, p* are parameters, the values of which have been determined experimentally *A*=1.3, *n*=2.25, *p*=0.232.
In general, the raindrop size distribution in the air differs from the distribution in the horizontal plane.

$$f_h(d)=\frac{f(d)v_t(d)}{\int_d f(d)v_t(d)\mathrm{d}d}$$

where $f_h(d)$ is the raindrop size distribution in the horizontal plane; *f(d)* is the raindrop size distribution in the air and, $v_t(d)$ is the terminal velocity of a falling raindrop with the diameter *d*.
Raindrops size distributions is in this paper used for the calculation of the global catch ratios. (in the part 3.4)

3 RESULTS AND ANALYSIS

3.1 Wind field

The prevailing winds in Belgium come from the south-west; therefore, this wind direction was chosen for the main investigation on our building.
A CFD simulation of the steady-state wind flow pattern around the reference buildings was performed with the Fluent 6.1 commercial software while choosing the RANS, realizable k-ε turbulence model and standard wall functions. The simulations were conducted with a tetrahedral grid, with 1.04 mil. control volumes, using logarithmic wind speed inflow profile (y = 0.03) and a wind speed of U_{10} = 10 m/s. The calculation domain size was 300 x 100 x 150 m (Fig. 3)

Figure 3. *Calculation domain*

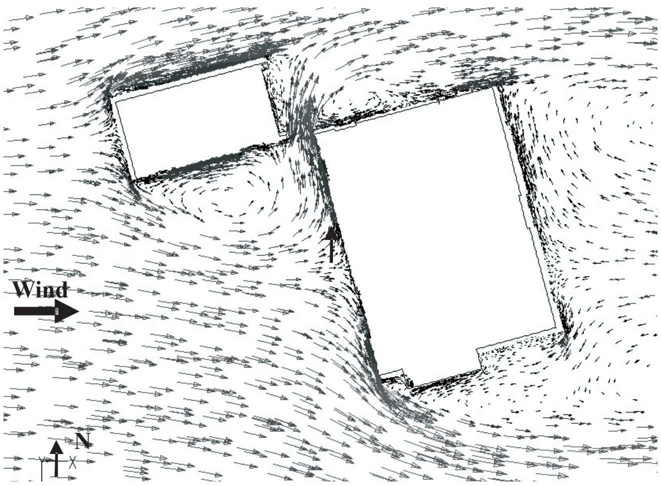

Figure 4. *Mean wind-speed vectors around the building, on a horizontal plane 1.75 m above the ground*

The results of the CFD analysis (mean speed values in the plane 1.75 m above the terrain) are given in Figure 4. The effect of the garage on the wind flow regime around the house is shown.

3.2 Rain drop trajectories

For the WDR analysis, the reference facade (10.9 x 3 m) was

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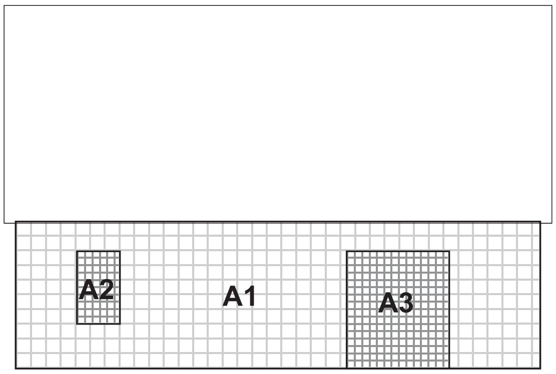

Figure 5. *Division of the reference facade into regions*

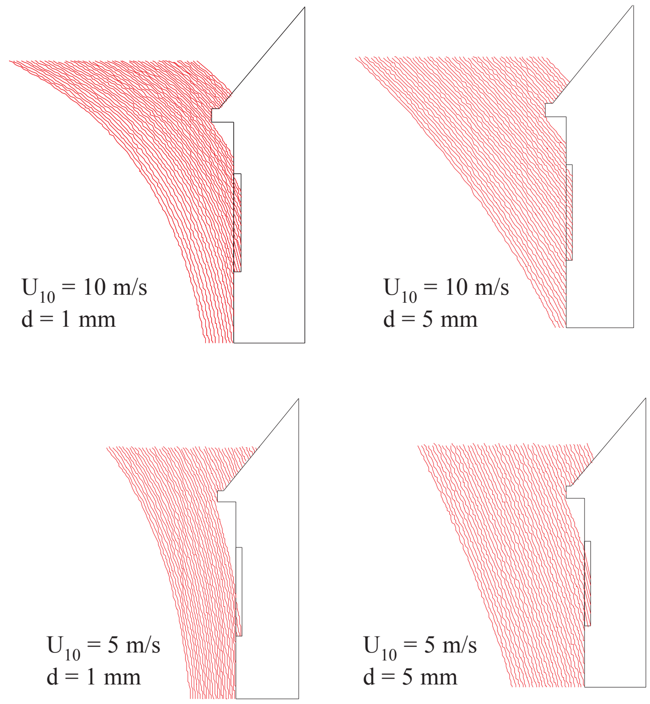

Figure 6. *Example of raindrop trajectories for raindrop diameters d = 1 and d = 5 mm in the wind speed U_{10} = 10 m/s and 5 m/s. The shelter effect of the roof overhang and window depth is observed.*

divided into three basic rectangular areas. (Figure 5) Area No.1 (A1) is the facade without any windows, Area No.2 (A2) is a window (0.9 x 1.4 m) with a window sill 1m above the ground. Area No.3 (A3) is a receding window (1.8 x 2.4 m) Raindrop trajectories for 8 wind-flow patterns with different wind speeds (1, 2, 3, 4, 5, 6, 8, 10 m/s) were calculated for 17 different raindrop sizes with diameters ranging from 0.3 mm to 6 mm (0.3, 0.4, 0.5 ,0.6, 0.7, 0.8 ,0.9, 1.0, 1.2, 1.4, 1.6, 1.8, 2.0, 3.0, 4.0, 5.0, 6.0 mm). The raindrops were equidistantly injected from the horizontal plane.

In general, trajectories are more inclined and distorted for small raindrops and higher wind speeds. For small raindrops, the effect of the garage on the WDR on the building facade was also observed. Trajectories are more rectilinear for larger drops and lower wind speeds.

In Figure 6 four examples of raindrop trajectories at window A2 are given. The effect of the wind speed and raindrop size on the trajectory is shown. The shading effect of the roof overhang is visible as well.

3.3 Specific catch ratios

Based on the results of the raindrop trajectories, the specific catch ratios η_d were calculated.

After an iterative determination of the trajectories that end at the corner points of the selected rectangular areas A1, A2, A3 of the building facade, a large number of raindrops from a dense, rectangular horizontal injection grid was injected. The catch ratios were calculated for 17 raindrop diameters and 8 wind speed values (as defined in part 3.2 of this paper).

Due to the effect of the roof overhang, a total cut-off for wind speed $U_{10} \leq 2$m/s was observed for the whole facade, i.e., for all the zones (A1, A2, A3). In the case of the A2 zone, the effect of the overhangs was even more pronounced, and there were no raindrops hitting this zone for windspeed values $U_{10} \leq 3$m/s.

The results of all the calculated catch ratios can be represented as an overall view of the distribution of the catch ratios η_d on the facade for all the combinations of wind speed and raindrop size.

For this article, the results of the specific catch ratios for wind speeds values 10 and 5 m/s and 1 and 5 mm raindrop diameters are shown in the Figure 7.

The effect of the overhang and the depth of the windows is visible in all results. It is also very obvious that the specific catch ratios over the facade are not symmetrical. This is due to the wind flow orientation, which is not perpendicular to the façade (the deviation angle of the wind direction from the normal to the facade is 15˚). The influence of the garage, which works as an obstacle to wind and rain, is noticeable on the left side of the facade as well.

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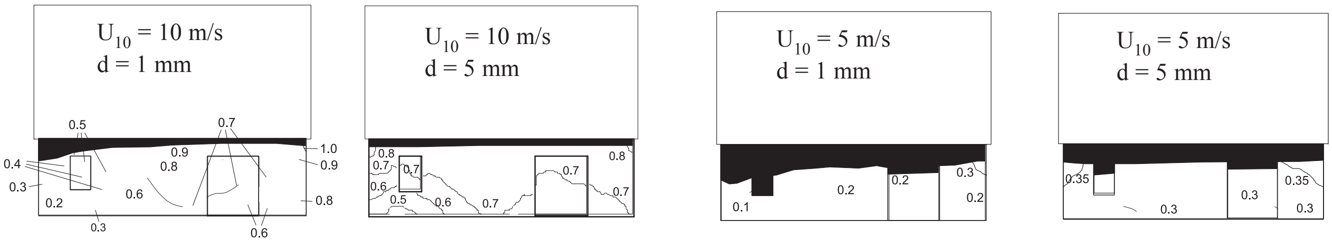

Figure 7. *Specific catch ratios η_d on the reference facade for different values of wind speed U_{10} and raindrop diameter d. The black areas are areas sheltered from rain.*

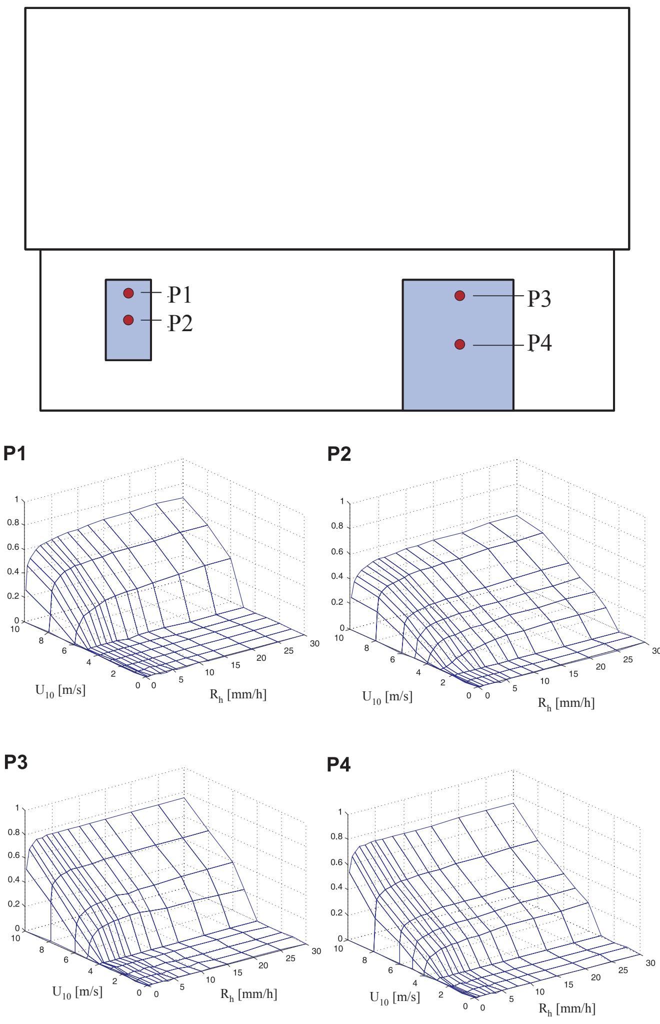

Figure 8. *Catch ratios η as a function of the reference wind speed U_{10} and horizontal rainfall intensity R_h for positions 1, 2, 3, 4.*

3.4 Global catch ratio

After having information about the specific catch ratios all over the facade, the raindrop-size distribution according to Best was used to calculate the global catch ratio η as a function of the wind speed U_{10} [m/s] and horizontal rainfall intensity R_h [mm/h].

The effect of the wind speed and the roof overhang appears to be very significant in the case of our reference building. In Figure 8, the global catch ratios as a function of wind speed U_{10} and rain intensity R_h for the four selected positions are shown.

In order to have a better overview of the catch ratio distribution on the facade surface, two examples were selected and are displayed in Figure 9. Both assume the rain intensity to be R_h = 1mm/h. The upper one is the situation for the wind speed with a profile of U_{10} = 10m/s, and the lower one for U_{10} = 5m/s. The areas on the facade where no rain occurred are colored black.

4 CONCLUSION

In this work, the direct WDR impact on a window and wall surface of a reference building facade was first simulated. The specific and global catch ratios were calculated for the south-west orientation of a wind flow, which was inclined 15˚ with respect to the facade.

From the results calculated, is quite evident that the building is protected from the small raindrops smaller than 0.4 mm for any speed of wind up to U_{10} = 10 m/s . These rain drops are carried by the wind around the building without touching the facade.

Heavy raindrops require a stronger winds to fall less vertically, e.g., to have more probability of hitting the whole facade, in the case of a building with roof overhangs. An example of a house with very common shape investigated in this paper has shown several the self protecting features, such an effect of the roof overhangs, effect of the reclined windows, effect of the

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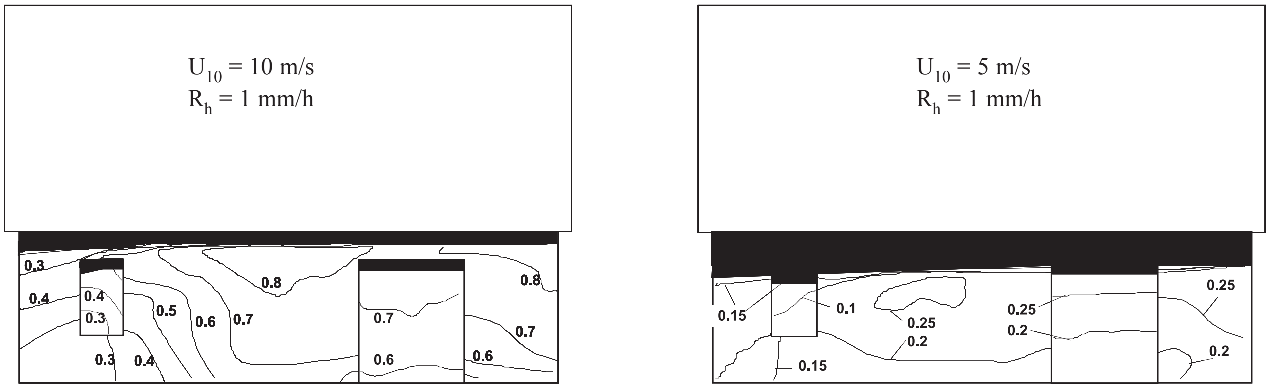

Figure 9 *Overview of the global catch ratios η on a reference facade for horizontal rainfall intensity R_h = 1mm/h. The upper picture shows the results for wind speed U_{10} = 10m/s and the lower one for U_{10} =5m/s.*

orientation of the house and the garage position with a respect to the prevailing wind direction.

Possibilities for future research can be seen in calculation of the global catch ratios for a house without self protecting structures and some work could be done in investigating the influence of the roughness of the walls and roof on the wind flow and global catch ratios.

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