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COMPUTER SIMULATION OF DRIVING RAIN ON BUILDING ENVELOPES

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ABSTRACT Driving rain is one of the important climatological factors which determine long-term use and durability of building envelopes. In this article a theoretical model for the calculation of driving rain is presented, by which the infuence of wind, building geometry and rainfall on the driving-rain intensity distributions on building envelopes can be studied.

In this model a catch ratio η is introduced which depends on raindrop diameter (D), reference wind speed (U) in the undisturbed wind flow, on building geometry (G) and on the position (P) on the building envelope. By the use of computational fluid dynamics catch ratios η for several wind speeds and geometries have been calculated. Subsequently, by use of $\eta(D,U,G,P)$, driving-rain intensities and its distribution on the envelope can be calculated with a chosen raindrop spectrum.

INTRODUCTION

Many factors determine the deterioration of building envelopes. Heat and moisture transfer, dry and wet deposition of chemical substances, design deficiencies and imperfections during building affect the performance and durability of facades, and the costs of maintenance. In order to design good buildings with regards to deterioration, knowlegde of the exposure to the local outdoor climate is primordial. One of the climatological parameters is driving rain.

The actual set of design rules and tools for building designers is small and rather inadequate. Only in the UK there is a standard for estimating driving-rain quantities [4]. Also for reseach on moisture transport in e.g. brick walls, more knowledge of driving rain is usefull, as driving rain is a major boundary condition.

For these both reasons, reseach on driving rain is taken up. This research implies both full-scale measurements (which will start in autumn 1997) and simulations by computational fluid dynamics (c.f.d.). In this article we show an approach by which computer simulations are useful for the understanding of the distribution of the impingments of raindrops on building envelopes, and for the estimation of driving-rain intensities.

DRIVING RAIN

Driving rain is rain which is carried by wind and driven onto the building envelope. The *free driving-rain intensity* R_v [mm h^{-1}] is the rate of rain falling through a vertical plane without the obstruction of the building. It is generally thought to be related to the horizontal rain intensity R_h [mm h^{-1}] and the reference wind speed U [m s^{-1}] as (figure 1):

$$R_v = \alpha\, U\, R_h. \tag{1}$$

The actual *driving-rain intensity* R_{dr} on the envelope is related to the free driving-rain intensity by a catch ratio κ [-], which depends on building geometry, drop spectrum and flow characteristics:

$$R_{dr} = \kappa R_v. \tag{2}$$

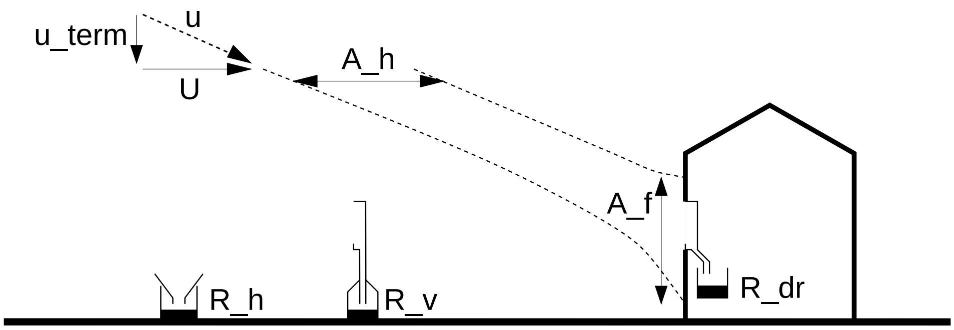


Figure 1: The dotted lines depict the trajectories of two drops with the same diameter which imping on a building. In the undisturbed flow (left) drops fall with velocity u, due to the terminal velocity u_{term} and the wind velocity U. Here, by rain gauges, the horizontal (R_h) and vertical (R_v) rain intensities can be measured; whereas on the building envelope the driving-rain intensity R_{dr} is measured. The catch ratio η (eq. 4) is defined by the areas A_h and A_f, by which the drop trajectories are characterised.

Lacy [13] concluded from his measurements and theory that the factor α is independent of wind speed and of horizontal rain intensity. For estimating driving-rain intensities he drew maps of driving-rain indices (d.r.i.), which depict the product of wind velocity and horizontal rain intensity (thus: d.r.i. = $U \times R_h$), based on local, yearly-averaged meteorological data.

British Standard BS 8104 for the estimation of driving-rain intensities [4] is based on equations (1) and (2), and follows Lacy's approach, yet refined by the use of hourly-averaged data and by the account of wind direction.

Frank [9] mentioned that Lacy's approach was not well suited for estimating driving-rain intensities in middle Europe. Frank referred to several experiments in which estimated driving-rain intensities differed substantially from measured driving-rain intensities.

There are other reasons to regard the equations (1) and (2) cautiously. Firstly, both the factor α and the ratio κ depend on the raindrop spectrum, so they are interdependent.

Secondly, the catch ratio κ is a complicated function of 4 factors:

$$\kappa = f(N, U, G, P), \tag{3}$$

with N = parameter(s) describing the drop size distribution, U = wind velocity, G = parameter(s) describing the building geometry and P = position on the envelope.

In the following section we will redefine the catch ratio, so that it is independent of raindrop spectrum. By doing this, we model raindrop trajectories and impingments on building envelopes as function of the above mentioned factors. To this end, calculations by c.f.d. have been performed. During the last five years one finds several articles with results of c.f.d. calculations of driving rain (e.g. [1], [5], [6], [11], [15]).

THEORETICAL MODEL

Figure 3 shows trajectories of drops with different sizes for a given geometry and wind speed. If one considers drops of the same size and if one assumes no turbulent dispersion, it is visible that drops form trajectories which are not crossed by aditional drops of the same size. One can

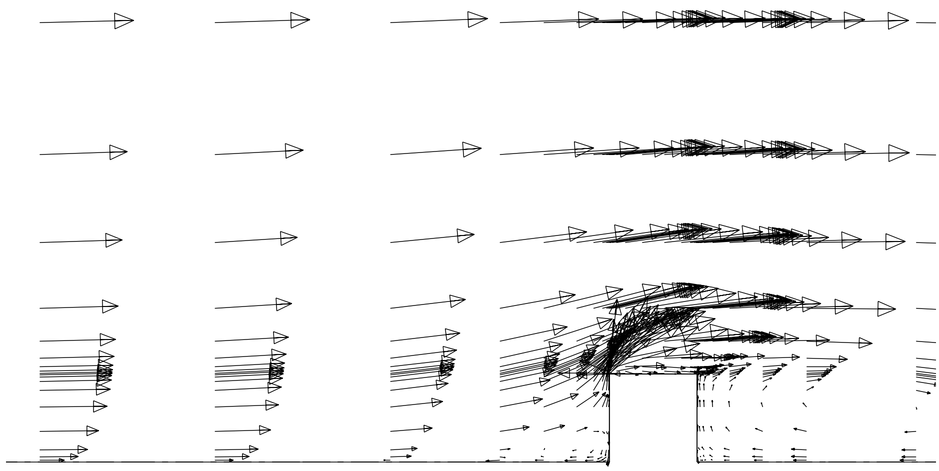


Figure 2: Calculated wind velocities around a building of 15 m height, 15 m depth and infinite length (U_{10} = 10 m s^{-1}, z_0 = 0.03 m).

thus define a (horizontal) area A_h in the undisturbed flow, through which drops fall before they imping on a certain area A_f on the building face (figure 1).

The ratio of A_h/A_f is the (redefined) *catch ratio* η [-], and it is a function of 4 factors:

$$\eta = f(D, U, G, P). \tag{4}$$

This relates to the driving-rain intensity R_{dr} [mm h^{-1}] by:

$$R_{dr} = 3600 \sum_D \eta(D)\, n_h(D)\, \rho \frac{\pi}{6} D^3, \tag{5}$$

with $n_h(D)$ = drop rate spectrum [m^{-2} s^{-1}], i.e. number of drops with diameter D [m] through a horizontal plane per square metre and per second in the undisturbed flow, ρ = density [kg m^{-3}] of water.

The catch ratio depends on the ability of rain drops to follow the curved and accelerating wind flow; due to deviations of the drop trajectories of the wind stream lines, drops imping on the building envelope. That ability depends, amongst other parameters, on the so-called stopping distance l_{stop} [16]. It is defined as the distance travelled by a drop as a result of its inertia, after that the driving force (the wind flow) is suddenly taken away. It is a function of drop diameter and initial drop velocity (which equals to wind speed in our case).

Turbulent dispersion of a raindrop will occur when vortices in the wind flow have greater dimensions than the stopping distance of the drop. In the atmospheric surface layer the integral lengths scale L_u is 50 to 300 m [10]. Although figure 4 shows us that generally $l_{stop} < L_u$, we do not (yet) account for it in our calculations.

CALCULATION METHOD OF THE WIND AROUND A BUILDING

Simulations of the wind around a building have been performed by a commercially available c.f.d. package *Fluent* (version 4.3). The used model is a standard k-ε model [8]. Some important features are as follows:

— The constants of the k-ε model have the values: $C_\mu = 0.032$, $C_{1\varepsilon} = 1.44$, $C_{2\varepsilon} = 1.92$, $\sigma_k = 1$ and $\sigma_\varepsilon = 1.3$.

  Only the C_μ constant has been adapted according to the findings of Bottema [2], who also compared his simulations with *Fluent* favourably with wind tunnel measurements.

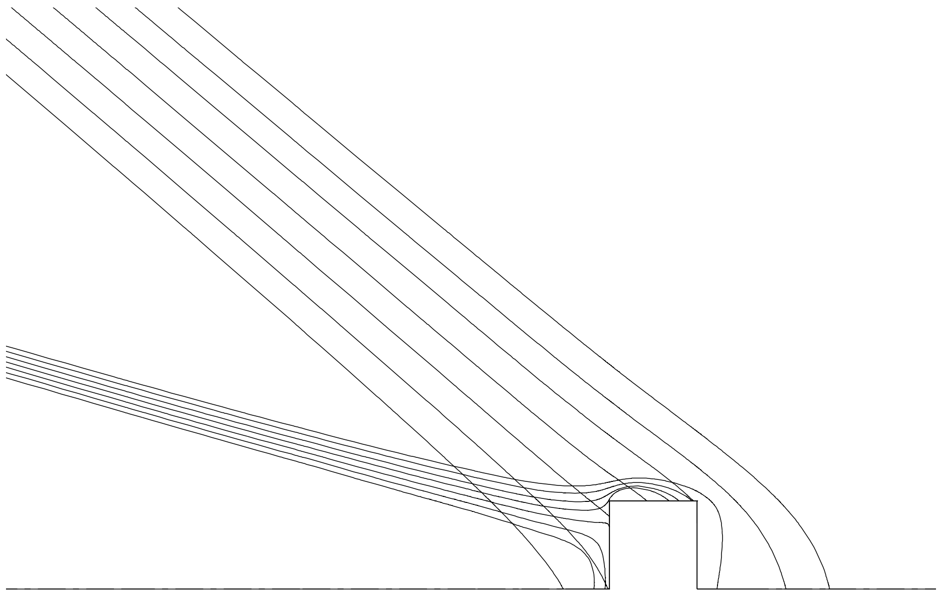


Figure 3: Calculated trajectories of drops with D = 1 mm and with D = 6 mm (same geometry and wind speed as in figure 2).

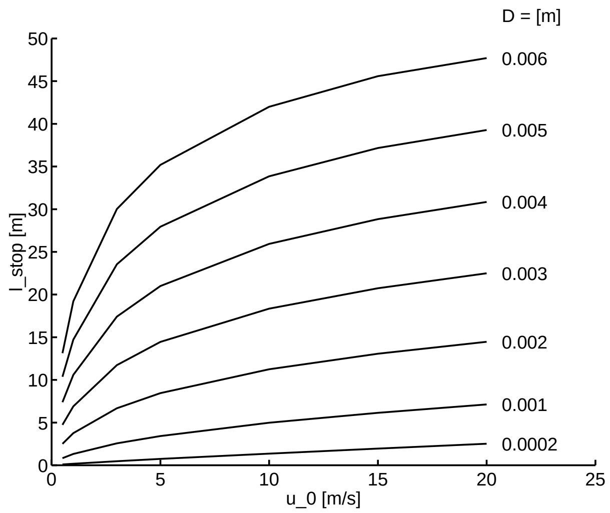


Figure 4: Stopping distance l_{stop} as function of drop diameter D and initial velocity u_0 (here equal to wind velocity U).

— The two-dimensional computational domain is 1200 m (depth) and 400 m (height), divided into approx. 65 resp. 25 cells depending on the geometry.
— The roughness height z_0 of the field is 0.03 m. z_0 of the building envelope is 0.0005 m.
— The wind profile of the wind coming into the domain is described by:

$$u = \frac{u_*}{0.4} \ln\left(\frac{z}{z_0}\right), \tag{6}$$

with u = horizontal wind velocity [m s^{-1}], z = height [m] above the field, and u_* = friction velocity [m s^{-1}] based upon the reference wind speed U_{10} on 10 m height on a field with z_0 = 0.03 m.
— Separation of the airflow at corners has been modelled by so-called 'link-cuts' (i.e. a feature of *Fluent* by which the wall-function in a computational cell is disabled).

In figure 2 an example is given of a simulation of the wind around a building of 15 m height, 15 m depth and infinite length.

CALCULATION METHOD OF RAINDROP TRAJECTORIES

The calculations of the raindrop trajectories have also been performed by the same c.f.d. package *Fluent* (version 4.3). The trajectories were calculated after the wind flow was calculated for a chosen geometry and reference wind speed. Dispersion of drops due to the turbulence of wind was not taken into account.

The motion of a raindrop is expressed by the following equation [8], [16]:

$$m\frac{d\vec{u}}{dt} = m\vec{g} - \frac{\pi}{8} C_d(Re)\, D^2\, \rho_a\, |\vec{u} - \vec{U}|\, (\vec{u} - \vec{U}), \qquad (7)$$

with m = mass [kg] of a raindrop, $\vec{u}$ = drop velocity vector [m s^{-1}], $\vec{U}$ = wind velocity vector [m s^{-1}], $\vec{g}$ = gravitational accelaration [m s^{-2}], C_d = drag coefficient [-] depending on the Reynolds number, Re = Reynolds number [-] = $D|\vec{u} - \vec{U}|/\nu_a$, ρ_a = density [kg $^{-3}$] of air, and ν_a = viscosity [m^2 s^{-1}] of air.

For the drag coefficient C_d the relation of Morsi and Alexander [14] is used.

A result of a calculation of raindrop trajectories in the flow of figure 2 is given in figure 3. Subsequently, catch ratios $\eta(D,U,G,P)$ can be calculated by determining A_h and A_f.

RESULTS AND DISCUSSION

Figure 5 shows calculated catch ratios $\eta(D,U,G,P)$ for the following configurations:

- two reference wind speeds: U_{10} = 5 m s^{-1} and U_{10} = 10 m s^{-1}.
- three geometries: (i.) a simple building of 15 m height, (ii.) a building of 15 m height and a canopy of 4 m at roof level, and (iii.) a building of 40 m height. All with a depth D of 15 m and infinite length (so no corner effects will be visible). In figure 7 the geometries are depicted.
- several positions: for convenience we look now only at two points on the windward facade: $z = 0.65\,H$ and $z = 0.95\,H$.

Choi [6] is the only reference found by us, who also gives calculated η's as function of (D,U,G,P) for several configurations. The shapes of Choi's graphs of $\eta(D)$ are very similar to ours. Unfortunately, the geometries are not comparable.

An important conclusion of figure 5 is that the catch ratio η is quite independent of drop diameters $D > 2$ mm.

The different graphs of figure 5 might be transformed and summarised into one graph by use of one or more parameters, e.g. the stopping distance. This is done by Bookelmann [1], but we found that his approach did not work satisfactorily for our configurations.

In figure 7 we show driving-rain intensities calculated from $\eta(D,U,G,P)$ by use of two measured raindrop spectra of Waldvogel [17]. In figure 6 these two raindrop spectra are depicted: spectrum A contains relatively more small drops, whereas spectrum B has more thick drops. This difference clearly effects the driving-rain intensities on the envelopes. The rain intensity ratio R_{dr}/R_h at corners increases with the number of thick drops. An other example of the effect of spectrum B is a higher rain intensity ratio under the canopy, because thick drops have more rectilinear trajectories.

Choi [6] and Karagiozis [11] also studied the influence of drop spectra and horizontal rain intensities on driving-rain intensities. They found that this is a very small effect, whereas in figure 7 we find a significant effect. The reason could be that the shapes of raindrop spectra used in their calculations are too similar.

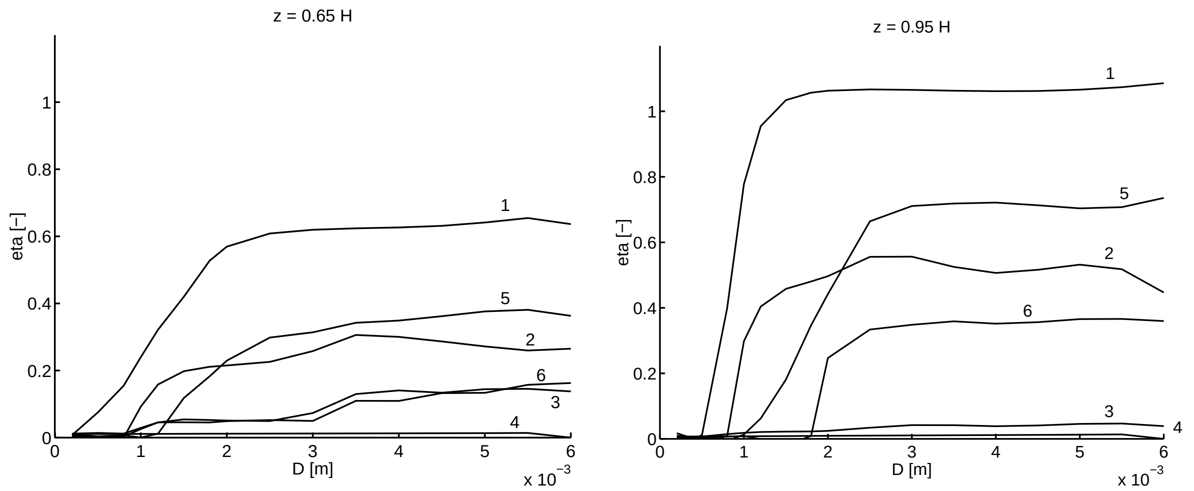
Finaly we compare the calculated driving-rain intensity ratios with those of full-scale measurements reported in literature (see e.g. [3], [7], [9], [12]). The reported parameter is often the catch ratio κ ($= R_{dr}/R_v$, eq. 2). In figure 7 we find κ's varying from 0.1 to 0.5 (assuming

$\alpha \approx 0.2$). This range agrees with the reported and measured κ's of 0.2 to 0.8 for the upper half of windward facades of various buildings.

CONCLUSIONS

A characterisation of drop trajectories and impingments of drops on building envelopes can be estimated by a catch ratio η as function of (D, U, G, P). It is a method to study and understand driving-rain intensity distributions on building envelopes, and hence it is a tool for the estimation of driving-rain intensities.

Further research will include investigations on the catch ratio for three-dimensional flow, on the influence of turbulent dispersion of raindrops and on parameters by which one can summarise $\eta(D, U, G, P)$ into a simple relationship, and will include full-scale measurements of driving rain.



1. H = 15 m, U_{10} = 10 m s^{-1}	2. H = 15 m, U_{10} = 5 m s^{-1}
3. H = 15 m with canopy, U_{10} = 10 m s^{-1}	4. H = 15 m with canopy, U_{10} = 5 m s^{-1}
5. H = 40 m, U_{10} = 10 m s^{-1}	6. H = 40 m, U_{10} = 5 m s^{-1}

Figure 5: Catch ratio η as function of drop diameter D, for two building heights H and reference wind velocities U_{10}, and for two positions at the windward facade, (left:) $z = 0.65\,H$ and (right:) $z = 0.95\,H$.

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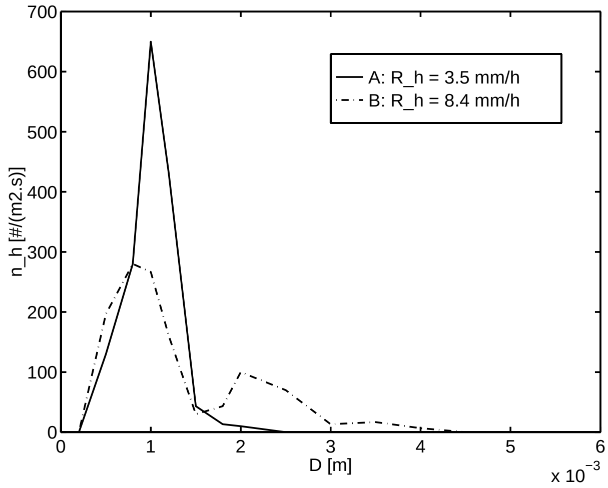

Figure 6: Two drop rate spectra n_h, measured by Waldvogel on 18 September 1969 at 15h44 (solid line; spectrum A) and at 15h49 (dashed line; spectrum B).

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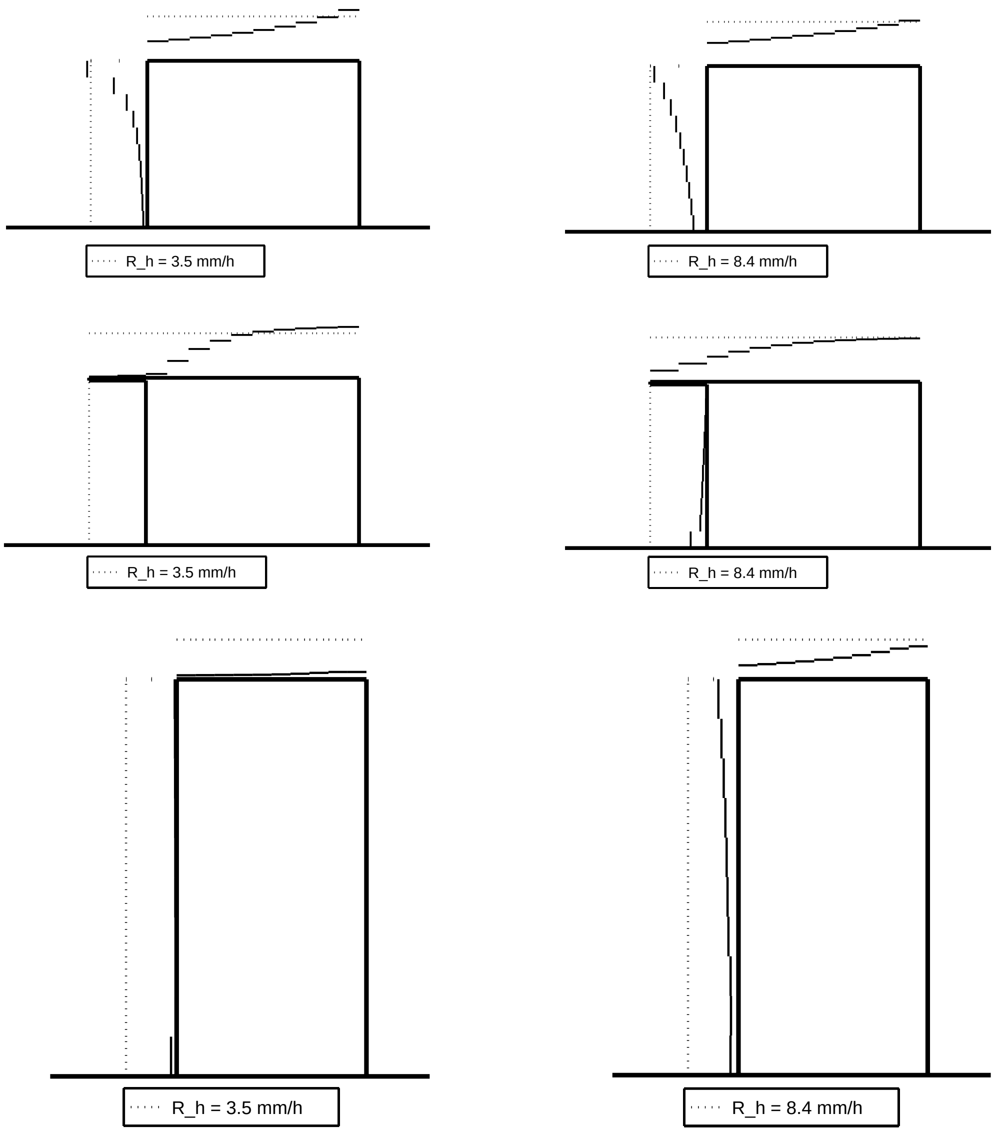

(A) (B)

Figure 7: Driving-rain intensity distributions on the windward facade and roof of three different buildings, due to rain with different spectra (see figure 6). The dotted lines indicate the horizontal rain intensity R_h: 3.5 mm h^{-1} (spectrum A, left graphs) resp. 8.4 mm h^{-1} (spectrum B, right graphs). The heights of the buildings are: (top:) H = 15 m, (middle:) H = 15 m with a canopy of 4 m, (bottom:) H = 40 m. All the buildings have depths D of 15 m and infinite lengths. The reference wind speed U_{10} is 10 m s^{-1}.