A plan for the measurement of driving rain on a building

Document status and date:
Published: 01/01/1996

Document Version:
Accepted manuscript including changes made at the peer-review stage

Please check the document version of this publication:

• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

Link to publication

A plan for the measurement of driving rain on a building

(paper for 3rd BEATRICE Euroconference in Nantes, 4–6 Sept. 1996)

Fabien J.R. van Mook

Eindhoven University of Technology, group Building Physics

Postvak 6, Postbus 513, NL–5600 MB Eindhoven

phone: +31–40 247 4899, fax: +31–40 243 8595, e-mail: famo@fago.bwk.tue.nl

3rd September 1996

Abstract

Many factors determine the deterioration of building facades. Heat, moisture, deposition of chemical substances, design deficiencies and imperfections during building affect the durability of facades, and of course the costs of maintenance. The research of which a plan is presented in this paper, is meant to give information on the outdoor (micro-)climatological conditions at building facades. The research is focussed on driving rain. The results will be used for other research e.g. on moisture transport in brick walls, and for design rules and tools for architects.

The aim is to measure driving rain on a building and to compare the measurements to calculations by computational fluid dynamics.

After approx. half a year of preliminary research there is quite a good overview of research done and being done on driving rain in the world. A short survey is given. Striking is that the methods of measuring driving rain have not changed much since its beginning in the 1930's. The traditional method is to collect driving-rain water by a flat tray mounted on the wall of a building.

This method has several drawbacks: evaporation of (little) drops (in the literature no investigation on it was found), and drop size distributions can not be derived from the measurements. Information on drop size distributions are very important to validate c.f.d. simulations of driving rain. The wind pattern around a building determines highly the trajectories of the rain drops, and so the wetting of the building facade.

The intention is to measure driving rain on several positions on the facade of the main building of the TUE. The measurement set-up of this, and of windspeed, is presented. The considerations will be discussed. As everything still is in a prelimary stage, comments are very welcome and can easily be taken into account.

Contents

1   Introduction

1.1 Problem definition

Many factors determine the deterioration of building envelopes. Inherent aging of the materials, cracks, water leakage, salt crystallization, mould growth, deposition of dirt and soot, washing-out of depositions and corrodation of metal fixtures are examples of deterioration. These are caused on one hand by the exposure of the building in the outdoor climate, and on the other hand by deficiencies and imperfections at design, building and maintenance.

To what extend deterioration should be prevented, depends on requirements such as safety, aesthetics, durability, use, building costs and maintenance costs. The first step in minimizing the deterioration is better design. Therefore a knowlegde of the exposure (in other words: the local outdoor climate) is primordial.

The goal of the research of which a plan is presented here, is to investigate one facet of the outdoor micro-climatological conditions at building facades, namely driving rain. This research is a phd research being done at the group of Building Physics of the faculty of Architecture, Planning and Building, at the Eindhoven University of Technology (TUE).

Driving rain is the rain which is carried by the wind and driven onto the building envelope. There are many kinds of deterioration, design and maintenance problems related to driving rain[1]. Results of the research should firstly be useful for the formulation of design rules and the development of better tools (c.f.d. simulations and laboratory tests) to assess driving-rain intensities. Secondly results should also be useful to other research, such as the calculation of moisture distributions in walls made of porous materials, the phemenology of salt crystallization in brick walls and the assessment of deposition of chemical substances on building facades. Driving rain is an important parameter, but it is still felt to be quite unknown. Therefore a measured data set of driving-rain amounts on a facade on hourly (or less) basis, and an assessment method should become available.

The main approach is to measure driving-rain intensities on a building during at least a year and to compare these to c.f.d. simulations.

1.2 Research set-up

The research is set up so that it will be able to give an answer on the following problems:

— A climatology with driving-rain data based on hourly (or less) measured statistics during one or several years is not yet available at the faculty. Because of limited means and time, measurements can be done on only one building.

— The error due to catch inefficiencies in the measurement of driving-rain intensities by the so-called « classical » driving-rain gauge has never been reported. An investigation should be done to determine this error.

— Systematic comparison between measurements of driving rain and c.f.d. simulations of a rain event have not been done (although several researchers have intentions to do that). For a good validation of c.f.d. results such a systematic comparison of results of different situations[2] should be done. Here, only one basic situation (one geometry, but in different weather) can be validated.

---

[1] Examples of subjects related to driving rain are: water penetration due to wind pressure, moist in walls and energy saving, cleaning frequency of windows, sheltering from rain (canopy roofs, bus shelters), architectural details related to rain-water run-off (sills etc.).

[2] I.e. for different building geometries, for different surrounding geometries, in different seasons and climates.

— Drop spectra are a special conditional parameter for c.f.d. calculations. The necessity of the measurement of drop size distributions for a good comparison between measurements and simulations will be investigated, and if necessary, drop spectra will be measured.

— The assessment of driving-rain intensities is still problematic. Better design rules and better tools (c.f.d. simulations and laboratory tests) should be developed, based on measured data. The design rules for architects may perhaps be improved by defining standard examples and d.r. catch ratios as function of the position on the facade, and in relation to weather type, surrounding characteristics and building forms. Measured data are very useful information for laboratory tests and computer simulations.

Therefore the research is split-up into the following phases:

1. literature study on driving rain and related topics,
2. literature study on methods for measuring driving rain; definition of specifications for d.r. gauges,
3. rough plan of the measurement set-up,
4. error estimation of classical d.r. gauges,
5. investigation in the necessity of the measurement of drop spectra,
6. design of a suitable d.r. gauge; preparation of the in-situ measurements,
7. measurements,
8. c.f.d. calculations, related to the measurement situation,
9. comparison and report.

The research is started in February 1996 and will take 4 years. The first 3 phases are more or less achieved. The aim of this paper is to give a brief summary of the results of the first 2 phases (sections 2 and 3), and to give the intentional plan for the measurement set-up (section 4). As this plan is in a preliminary stage, comments are very welcome and can easily be taken into account.

2   Literature survey

2.1   Developments till 1970

Driving rain has been the subject of research for many years. Main surveys can be found in [Lacy 1965], [Frank 1973] and in [Prior 1985]. In this section the historial developments are briefly summerized.

The oldest instrument (according to Middleton [1969]) which determines the direction from which the rain is coming, was made in 1816. It was a so-called « vectopluviometer » and had a horizontal opening and a vertical opening which faced into the wind by a vane. So, it measured —as we now would call it— the free driving rain. One has to wait until 1937 when prof. Holmgren performed measurements of driving rain on a facade with a shallow square tray fixed to the wall of a building in Trondheim. This method is called the « classical » one: rain water is collected by the tray and guided into a bottle (figure 1). Similar gauges are still used today. During the second World War Chr. Nell measured driving rain on houses in a street in Voorschoten (NL). Basart [1946] reported the findings of Nell who compared the driving-rain results measured by two different methods: by a classical gauge and by regular weighting of a plate made of very aborbent bricks (« hardgrauw »). Differences were attributed to measurement anomalies and to the variation in the rain drop size distributions, changing from one storm to another.

In the fifties and sixties many investigations were done. Firstly, work was done to improve and standardize the driving-rain gauge. Different institutions designed their own gauge, varying in diameter (10–45 cm), in material and in finnish (regarding the use on a wall or instead of a window, or regarding to disturbence of the wind flow). Within the CIB one tried to define standard gauges.

Secondly, more systematic measurements, over years and on different locations were done. The most active countries were Britain, Denmark, Norway and Germany.

Thirdly, theorectical considerations led to the *driving-rain index* approach of Lacy [1965] (see also: [Lacy 1977]). He used the following relationship between the free driving-rain (vertical) intensity and the horizontal rain intensity:

$$R_{\text{free dr}} = \alpha \, U_{\text{met}} \, R_{\text{met hor}}, \tag{1}$$
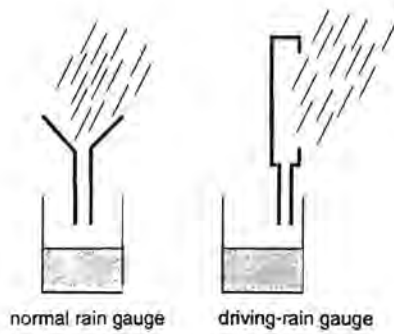
3

normal rain gauge   driving-rain gauge

Figure 1: Rain gauges: (left) for normal rain (i.e. vertically falling rain), and (right) for (free) driving rain. The latter can be mounted on a facade: the classical driving-rain gauge.

with $R_{free\ dr}$ = the free driving-rain intensity [mm/h] (without any obstacle), U_{met} = the free windspeed [m s^{-1}] at 10 m height and $R_{met\ hor}$ = horizontal rain intensity [mm/h] in the undisturbed wind field. The product of U_{met} and $R_{met\ hor}$ is known as the *driving-rain index*. For Britain and other countries, d.r.i. maps were provided, based on already existing yearly averaged meteorological statistics.

Lacy calculated that α is 0.2 s m^{-1}. For his calculations he assumed that

— rain is homogeneous and stationary. I.e. the drop size distribution is constant at every position;

— drop velocities are totally addapted to the wind velocity;

— there is a relationship between the terminal drop velocity and the rain intensity: $u_{term} = 4.505 R_{hor}^{0.123}$.

It is clear that for driving rain on building facades these assumptions are not obvious. Therefore a catch ratio is defined:

$$R_{dr} = \kappa\, R_{free\ dr}. \tag{2}$$

The problem of driving rain was discussed internationally within the working groups of the CIB and during two symposia in 1965 (RILEM/CIB symposium in Helsinki) and in 1974 (RILEM/CIB symposium in Rotterdam).

2.2   1970 – 1990: Doubt and stagnation

Whereas the period between 1936 and 1970 can be characterized as a period of constructive developments, the following two decades have been less productive. The state-of-the-art described in [Frank 1973], [Schwarz 1973] and in [Lacy 1977] remained quite actual until the end of the eighties.

Quite early it became clear that the d.r.i. method of Lacy was not well applicable for estimating driving rain in some situations. Frank [1973] already mentions that the driving-rain index is not applicable in middle Europe, because of its different climatology and topology, compared to the British Isles and Scandinavia. Perhaps, because wind velocity, direction and rain intensity in maritime climates with relatively flat topologies are less correlated to seasonal changes, the use of driving-rain index based on annual meteorological statistics, might be a reasonable first estimation.

While in the United Kingdom during the eighties preparations [Prior 1985] were made for a British Standard based on a refined approach of Lacy[3], a special approach for central Europe did not made its appearance. The approach in Britain was criticized, but nothing new came up and the research then seemed to stagnate.

2.3   Developments after 1990

New possibilities of computational fluid dynamics gave a new push to the study of driving rain. New researches were undertaken and the main features can be summarized by the following:

---

[3] The standard was established in 1992 by BS 8104 [BSI 1992]. The d.r.i.'s were now based on hourly averaged statistical data. A « rain spell index » was introduced to give an estimation for the worst possible amount of rain water fallen during a spell (i.e. a period of a rain event or several closely related, successive rain events).

Table 1: Summary of publications after 1990 with a general abstract of their contents.

	d.r. measurements
[Fazio et al. 1995], [Henriques 1992], [Hens and Mohamed 1994], [Künzel 1994a], [Künzel 1994b], [Matthews et al. 1996], [Sankaran and Peterson 1995], [Surry et al. 1994], [Zhu et al. 1995]	Different buildings in different climates. Method: classical driving-rain gauge. Measured $\kappa \times \alpha$ is very variable and ranges from 0.01 —at lower part of a building face— to 0.14 —at the upper part. At edges $\kappa \times \alpha$ might even be 0.8.
[Osmond 1995], [Osmond 1996]	Combination of measurement of wind pressure, wind velocity and of driving rain on several positions on the facade of a building.
	windtunnel experiments
[Surry et al. 1994]	The wetting of a scalled building is studied qualitatively and in future quantitatively.
	computer simulations
[Choi 1993], [Choi 1994a], [Choi 1994b], [Choi 1994b], [Choi 1994c], [Choi 1995]	Calculated driving-rain intensities due to a stationary wind pattern. Influence of building dimensions, wind speeds (also wind gusts) and horizontal rain intensities are studied on the wetting pattern on the faces of a tall building. $\kappa \times \alpha = 0.05$. Interest is mainly in extreme high rain intensities.
[Sankaran and Paterson 1995]	Influence of wind turbulence on drop trajectories and driving-rain intensities. (Calculations by k-ϵ model.)

— Use of c.f.d. simulations. Wind flow pattern around a building is calculated, most often by a k-ϵ turbulence model. Subsequently drop trajectories are calculated and the position of impingment on the building envelope is determined.

— The approach is not statistical (based on annual data), as for the d.r.i. method, but one studies the driving rain during a (stationary) rain event.

— The aim of some of the researches is focussed on the assesment of the micro-climate around buildings and on investigation of water penetration, in both cases for the sake of defining suitable laboratory tests on facade elements.

Such an aim is nothing new, but it is emphasized due to the growing interest in durable design of facades and in certified quality of facade elements. At least in Europe such research is stimulated and partly coordinated by CEN for the formulation of a European standard [Matthews et al. 1996].

— For general insight and for supporting computer simulations scaled experiments in windtunnels are performed, see e.g. [Surry et al. 1994]. Recently a hudge windtunnel is built, so that experiments with wind, driving rain and even with sand can be done in full-scale [Gandemer and Barnaud 1995].

In table 1 a summary is given of the latest contributions to the literature.

2.4 Conclusions and considerations

The following conclusions and considerations can be drawn from an overview of the literature:

— The results, though often preliminary, of full-scale and scaled experiments and of simulations in similar situations, are roughly comparable.

— Comparison of results by full-scale, scaled and simulation methods would be better (i.e. in more detail) possible, if per situation the three methods are applied.

— Input data for simulations and windtunnel experiments have not yet been provided. Especially one should take care of data on drop spectra and wind profiles, and their respective temporal evolutions.

— The built environment is very complex in its variety of geometry, climatology and use. It is quite difficult to provide simple rules of thumb to assess driving-rain intensities for different parts of the building envelope. A possibility could be to give assessment rules for the catch ratio κ as function of the position on the facade, depending on building dimensions and orientation, and taking into account the variability of the weather. Designing durable facade details, an architect should then give special care to the positions with a certain catch ratio.

Whether a design of a building facade would withstand the environmental requirements, can be evaluated by laboratory tests or c.f.d. calculations. Good validation of c.f.d. calculations and suitable data sets for such tests needs a lot of measured data of many different situations, which is still lacking.

3 Driving-rain gauges

3.1 Principles

As already is stated in section 2.1, the so-called « classical » driving-rain gauge consists of:
— a collection plate (a shallow tray) fixed to the wall of a building. The drops hit the plate, drip downwards and are collected by:
— a drainage channel, which leads the collected rain water to:
— a bottle or a water flux gauge. By the latter one measures the instataneous driving-rain intensity.

Such a driving-rain gauge has several drawbacks. The catch efficiency can be reduced due to splashing-out, drops which keep « stuck » on the collection plate, evaporation of drops, and the catch efficiency can be reduced due to extra disturbance of the wind pattern due to the form of the collection plate. No article is found which deals with this problem. Moreover, by the classical method it is impossible to measure drop size distributions.

To see whether a new technique could be possible, a literature study is done. A survey is given in table 2 and figure 2. Most of the methods mentioned in table 2 are commercially available (except for nr. 5, 6 and 8). In the next subsection specifications for an ideal method of measuring driving rain are mentioned to give an aid to an appropriate choice.

3.2 Specifications

The specifications of a method for measuring driving rain are;
- the measuring range of R, and for disdrometers, also in a;
- the accuracy in R and, for disdrometers, also in a;
- the temporal resolution and averaging;
- a representative sample of the actual driving rain on the actual position on the building envelope should be measured. This can be characterized by:
  — the position of the measuring volume relative to the envelope.
  — the area of the measuring volume, parallel to the envelope,
  — the thickness of the measuring volume, for eventual velocity measurements by a disdrometer,
  — the catch efficiency, regarding to splashing-out, blowing away, and evaporation of the impinging drops, and regarding to extra disturbence of the wind pattern;
- use requirements: automated registration, automated emptying of the reservoir, drift of signals, ease of maintenance, ease of mountability, costs, etc.

Table 2: Methods for the measurement of rain and eventually suitable for the measurement of driving rain.

method	measures	principle	reference
1. rain gauge with a drop counter	$R(t)$	in the reservoir is a little hole, by which drops of a certain diameter are formed; these are counted	[Schwarz 1973]
2. rain gauge with a float	$R(t)$	water level of the reservoir is registered	
3. rain gauge with a tipping bucket	$R(\Delta t)$	every time the bucket tips, a certain amount of water has passed through	
4. capacitive rain gauge	$R(\Delta t)$	by an electrode the level in a small reservoir is measured	[Schwarz 1973]
5. rain gauge with balance	$R(t)$	the (added) amount of water in the reservoir is weighted	
6. rain gauge with an absorbent material	$R(\Delta t)$	rain drops are absorbed by the material, which is regularly weighted	Chr. Nell (mentioned in [Basart 1946])
7. dyed filter paper method	$n(a)$	drops fallen on specially prepared paper, make stains, of which the diameter is a function of drop size and drop velocity	[Wessels 1967]
8. photographical / video method	$n(t)$	drops fallen on a glass plate are registered	
9. Joss-Waldvogel disdrometer	$n(a)$	the impulses of drops falling on a horizontal plate are measured	[Joss and Waldvogel 1967]
10. shadow disdrometer	$n(a)$	drops fall through a light sheet; their shadows are detected by photodiodes	[Knollenberg 1970], [Schönhuber et al. 1994]
11. diffraction disdrometer	$n(a)$	the diffractive pattern of drops falling through the light sheet depends on quantity and size of the drops	(Malvern Mastersizer)
12. scintillation rain gauge	$R(t)$	drops falling through a light sheet cause scintillations («twinkling» of the light); the form of the frequence spectrum is correlated to rain intensity by calibration	[Wang et al. 1978], [Wang 1982]
13. Doppler-radar disdrometer	$u(a)$	the Doppler signal of a radar yields drop velocities	[Sheppard 1990b]

Information to formulate specifications can be found in:

— measured drop size distributions. Unfortunately not much concrete data are available. We used the data mentioned in [Winkler 1993], see figure 3. One sees for example that the shape of the drop size distribution changes quite rapidly: the total number of drops falling through the horizontal plane can rise from 300 in the first minute till some 4000 after 5 minutes. To say something about the evolution of drop spectra during rain events, and to be able to average correctly from very variable
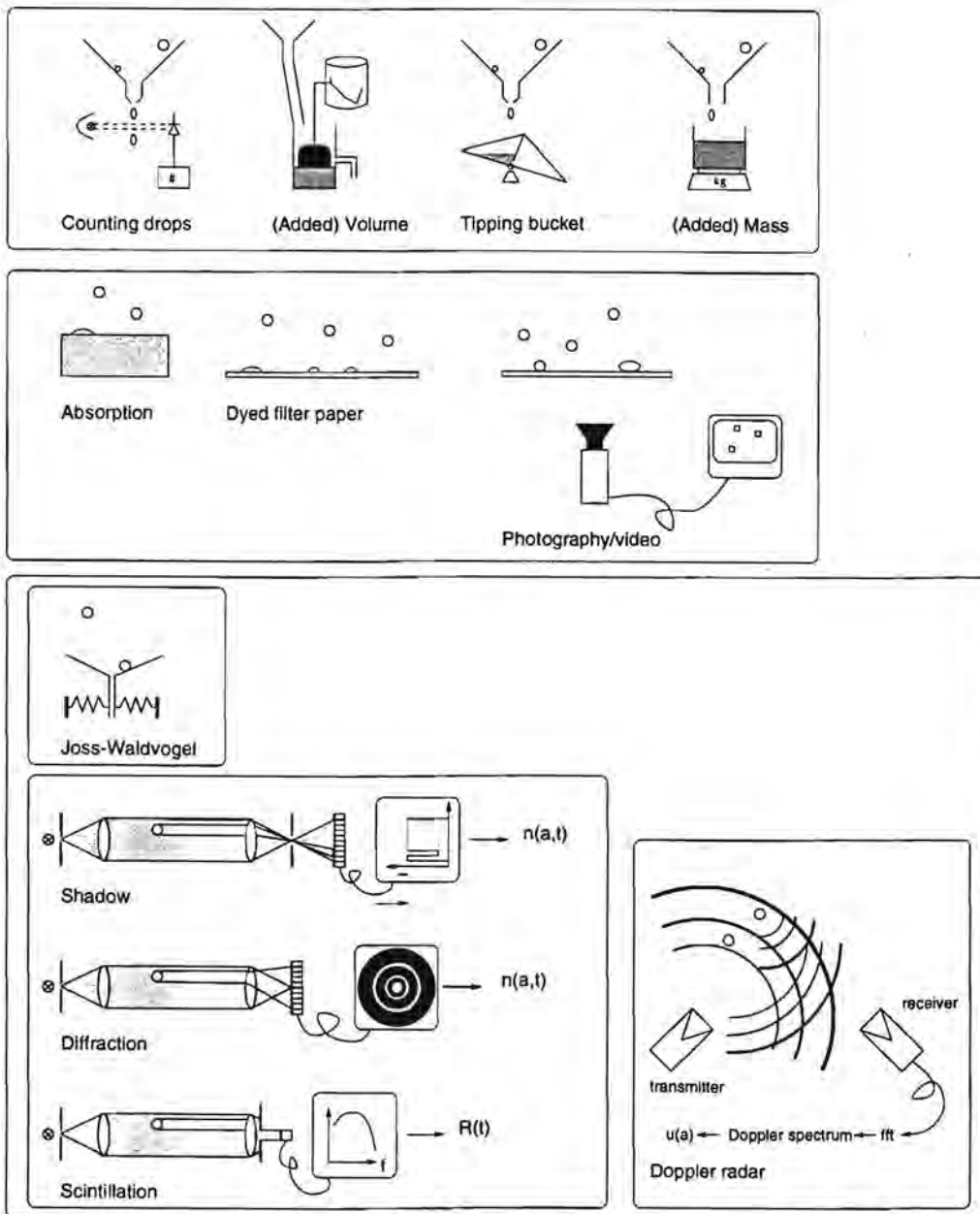
Figure 2: Principles of measurement principles for (driving) rain.

drop spectra, one may assume from these measurements that the sample frequency should be at least 1 min.

Figure 4 depicts the calculated normalized drop mass distributions, and shows that it is important to catch rain drops of at least 0.3 mm in radius for accurate measurements of drop spectra during the first minute of the beginning of a rain event.

One remark should be placed here. It is for us now impossible to see whether the drop spectra of [Winkler 1993] could be somehow representative for the situation and weather in which we will measure, because place, windspeed and rain type of Winkler's measurements are unknown to us;

— hourly averaged meterological data over several years (of De Bilt (NL)). The national meteorologic institute KNMI provides these quite detailed data of rain sums (through a horizontal plane) during the clock hour, times of rain during the clock hour, hourly averaged windspeeds, wind directions etc. Analysing the data gives an idea of (distributions of) occuring rain intensities and durations of rain events in relation to windspeed and wind direction;
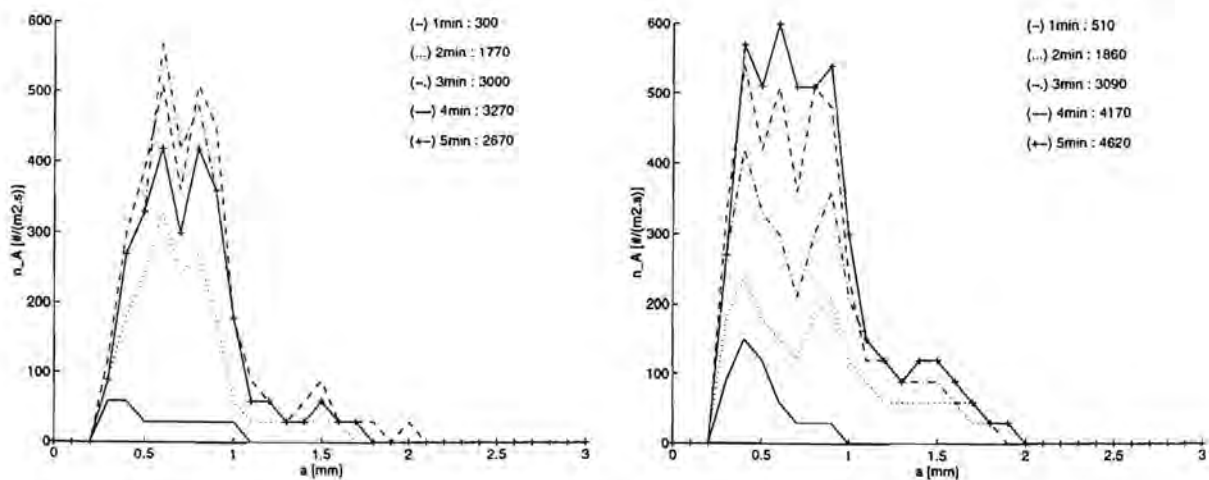
Figure 3: Averaged drop size distributions (n_A) of the first five minutes after the beginning of 60 rain events in November 1986 (left) and in September 1987 (right). The distributions were measured by a Joss-Waldvogel disdrometer. In the upper right corner of the figures the total number of drops (N_A [m^{-2} s^{-1}]) is given. The rain intensity in the first minute is 1.4 mm/h (Nov.) and 1.3 mm/h (Sep.); in the fifth minute: 26 mm/h (Nov.) and 57 mm/h (Sep.).
[Winkler 1993]

Table 3: Main specifications for a driving-rain gauge.

measuring range R	0.05 ... $\geq$ 2.0 mm/h
accuracy R	$\leq$ 10%
sampling and averaging time	0.1 Hz resp. 1 min
measuring area	$\sim$ 0.5 m^2 (*)
catch efficiency	$\sim$ 90 % of drops with a = 0.3...3 mm
max. rain sum (3 days)	$\geq$ 5 mm (**)

(*) The choice of a measuring area affects the accuracy. The greater the area, the greater the collected amount of rain water, which can be measured more easily.

(**) If the gauge collects rain water in a reservoir, the reservoir should not too often be emptied manually. For that one may assume that the reservoir should not be emptied when less than 5 mm has fallen onto the collection plate.

— measured driving-rain intensities on buildings. In literature (among others: [Frank 1973], [Hens and Mohamed 1994], [Künzel 1994a; Künzel 1994b], [Lacy 1977]) one mentions the measured relationship between windspeed, free driving rain and driving rain on facades. These are expressed by α and κ in the equations 1 and 2. In general one finds a value of 0.01 to 0.14 s m^{-1} for $\alpha \times \kappa$;

— calculated driving-rain intensities on buildings. In [Choi 1994b; Choi 1994c] it is found by c.f.d. that $\alpha \times \kappa$ is approximately 0.05 s m^{-1}.

Assuming $\alpha \times \kappa$ = 0.05 and using the data of De Bilt, one can calculate the frequency of driving-rain intensities. Figure 6 (relative frequency spectrum of driving-rain intensities) on a west facade shows that d.r. intensities are very low, most often below 0.2 mm/h, and that the measuring range for a relatively accurate driving-rain gauge should be able to measure intensities of 0.05 mm/h and more. Moreover, calculations, with the assumption that d.r. intensities of 0.05 mm/h and less could not be detected, show that the error in the monthly and dayly d.r. sums is less than 10%.

In table 3 one finds the « ideal » specifications for a driving-rain gauge. These are based, amoung others, on the above mentioned information and considerations.
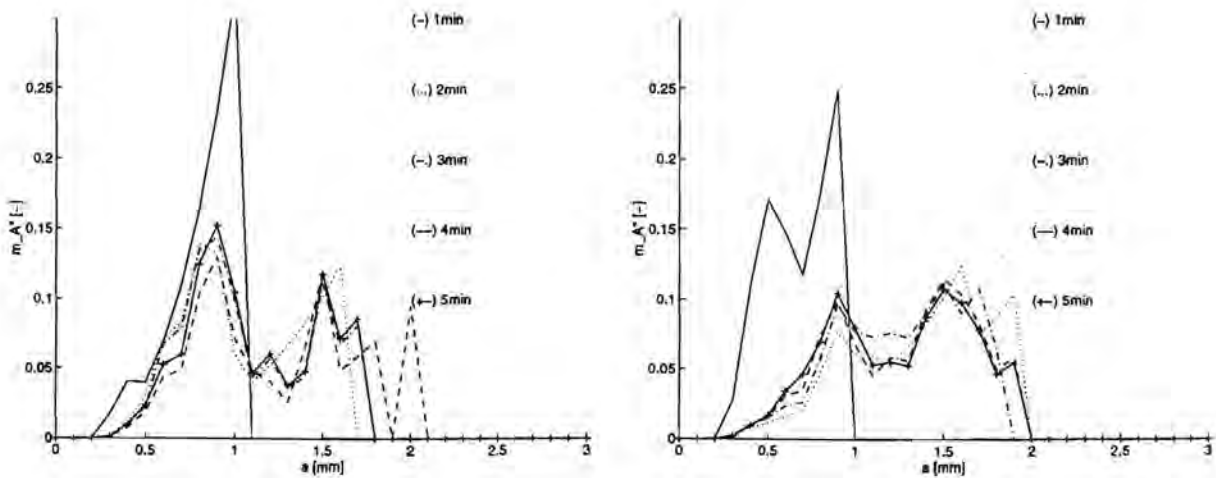
Figure 4: Normalized drop mass distributions (m_A^*) of the distributions in figure 3. Left: November 1986, right: September 1987.
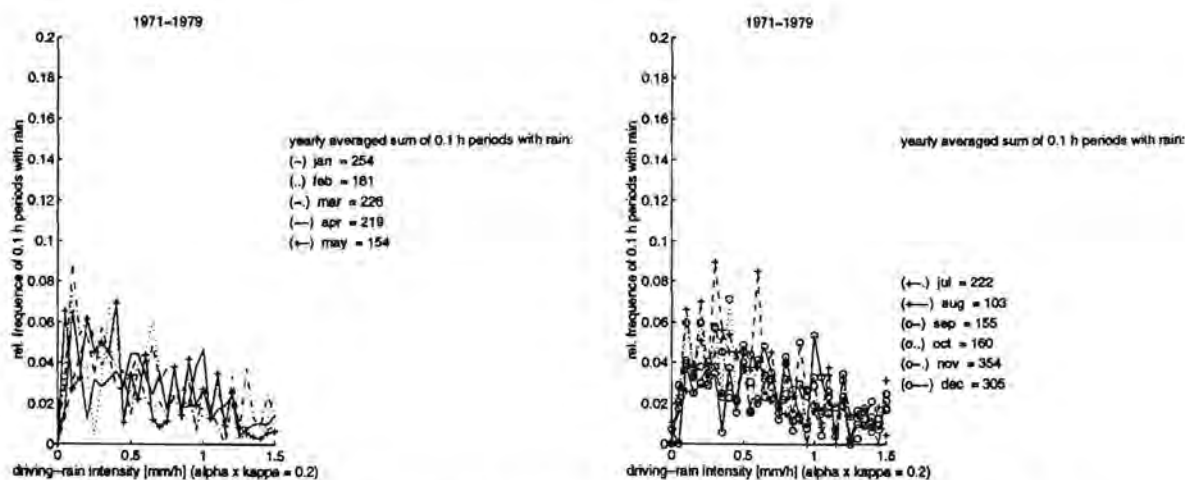

Figure 5: Relative frequency of driving-rain intensities over 9 years, for $\alpha \times \kappa = 0.2$ and for winds from 270 ± 60 degrees. In the plot also the yearly averaged total number of 0.1 h periods with rain is given.

3.3 Choosing the suitable device

The specifications in table 3 are the most important functional ones, but they leave many possibilities open. Regarding the d.r. gauges, there is therefore the intention to do some laboratory experiments for the design of a suitable gauge which can easily be mounted on the desired building facade. The principle of the classical gauge will be applied, but aspects like the catch efficiency regarding to evaporation and splashing-out and the method of measuring the collected water flux will be studied. Also verification of the future measurements by the use of different gauges will be considered.

Regarding the driving-rain spectra, the most suitable measurement principle seems to be the shadow disdrometer, for which a configuration for either driving or normal rain is conceivable. But commercial devices of this principle are very expensive. In general one should note that the difficulties of the measurement of drop spectra of normal rain are many (see e.g. [Sheppard and Joe 1994] and, for the oldest method, the Joss-Waldvogel disdrometer, e.g. [Sheppard 1990a]). If it can be proven that measurement of drop spectra of normal rain on the reference position is necessary, a Joss-Waldvogel or a simple optical disdrometer will be used.
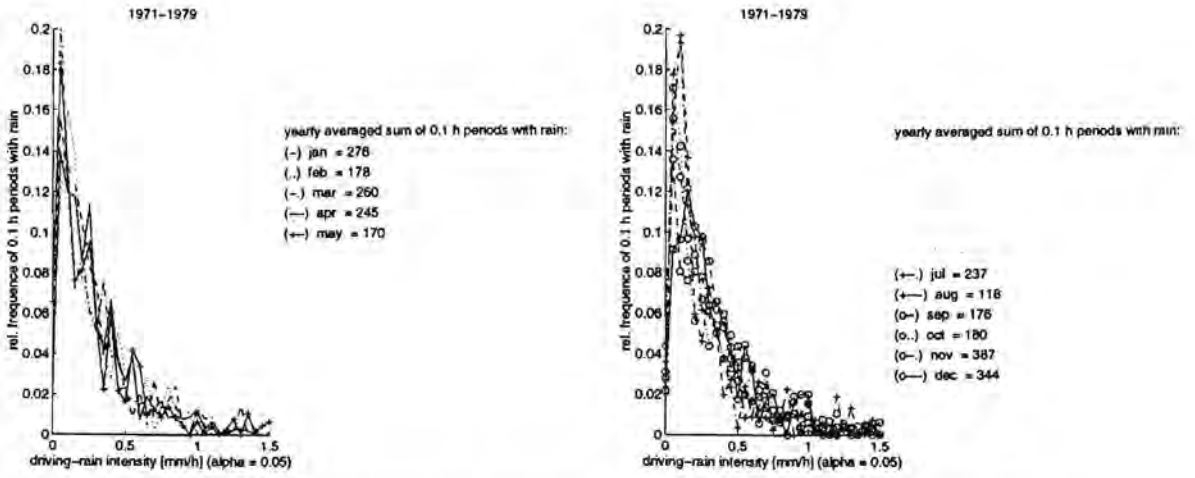
Figure 6: Relative frequency of driving-rain intensities over 9 years, for $\alpha \times \kappa = 0.05$ and for winds from 270 ± 60 degrees. In the plot also the yearly averaged total number of 0.1 h periods with rain is given.
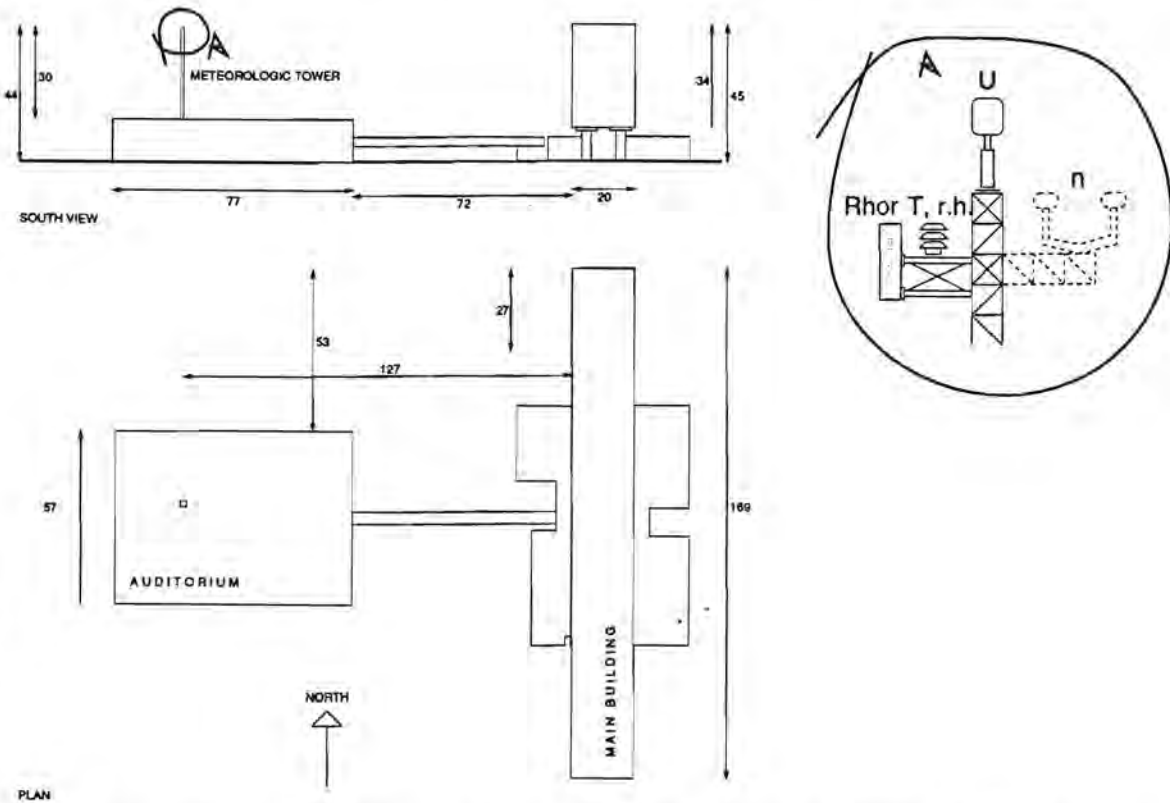
Figure 7: South facades and plan of the the Main Building and Auditorium of the TUE. On the reference location, on the meteorological tower (indicated by A), windspeed, rain intensity and eventually drop spectrum are measured.

4 Measurement set-up

4.1 Principle

While below a concise sommation of the different aspects and considerations of the planned measuring set-up is given, the reader is referred to the figures 7, 8 and 9:
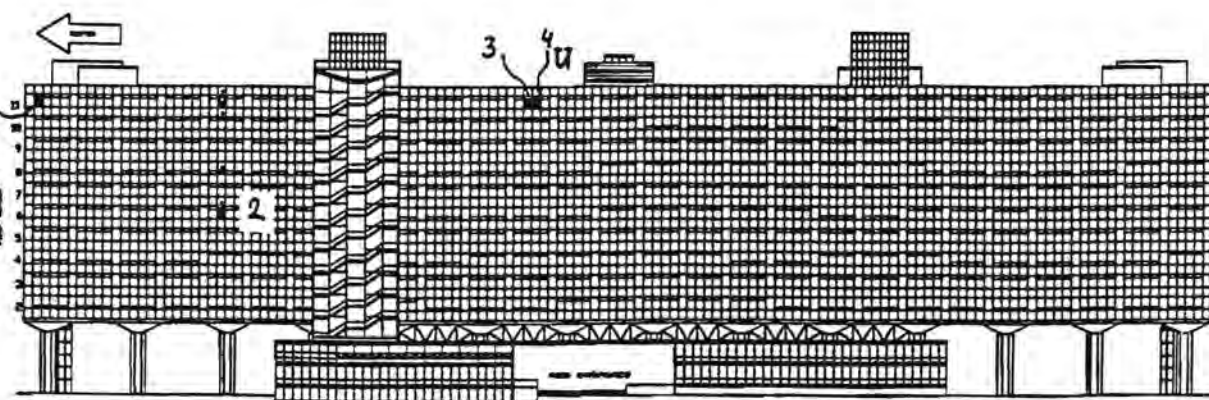
Figure 8: West facade of the Main Building of the TUE, with indications of measurement locations for driving rain. At position U also the windspeed at the facade will be measured.

- The experimental building is the main building of the Eindhoven University of Technology. Advantages of the use of this building are: (1) wind from the west is not much affected by neighboring buildings, (2) there is a meteorologic tower for the reference windspeed and rain intensity at 127 m from the west facade, (3) the facade consists of window and parapet elements on which collection plates can relatively easily be mounted, there is also a possibility to put devices inside, (4) the university population does not have problems with the presence of measuring devices and cables in the offices. Moreover, the building is already in use for measurements of wind-induced pressures on the facade [Geurts 1994].
- Five measurement locations are foreseen:
  - the reference location on the meteorological tower (see figure 7), where U, R and eventually $n(a)$ will be measured.
  - three locations on the west facade of the main building (see figure 8), where R_{dr} is measured,
  - one location on the west facade, close to one of the three other locations, where U and R_{dr} are measured. This gives the opportunity to verify the measurement of R_{dr} by two different driving-rain gauges.

  In figure 8 the four measurement locations on the facade are indicated.
- Measuring devices will be:
  - for the windspeed: sonic anemometers;
  - for the drop spectra on the tower: a Joss-Waldvogel disdrometer or an optical disdrometer;
  - for the horizontal rain intensity on the tower: a capacitive rain gauge;
  - for the driving-rain intensity: classical d.r. gauges with a drop counter or a balance.
- As weather is very capricious, automatic data aquisition and storage is important. The data aquisition system will have two modes: a slow and a fast operation mode.

  During the slow operation mode (i.e. the usual mode) the system
  - measures the windspeed on the tower,
  - registers the windspeed and direction in 10 min-averaged format plus standard deviations,
  - keeps up the output signal of the rain gauge and the disdrometer on the tower to detect rain,
  - switches to the fast operation mode, if rain is detected.

  In the fast operation mode the system
  - measures the windspeed, rain intensity and drop spectrum on the tower,
  - measures the windspeed and driving-rain intensities at the locations on the facade,
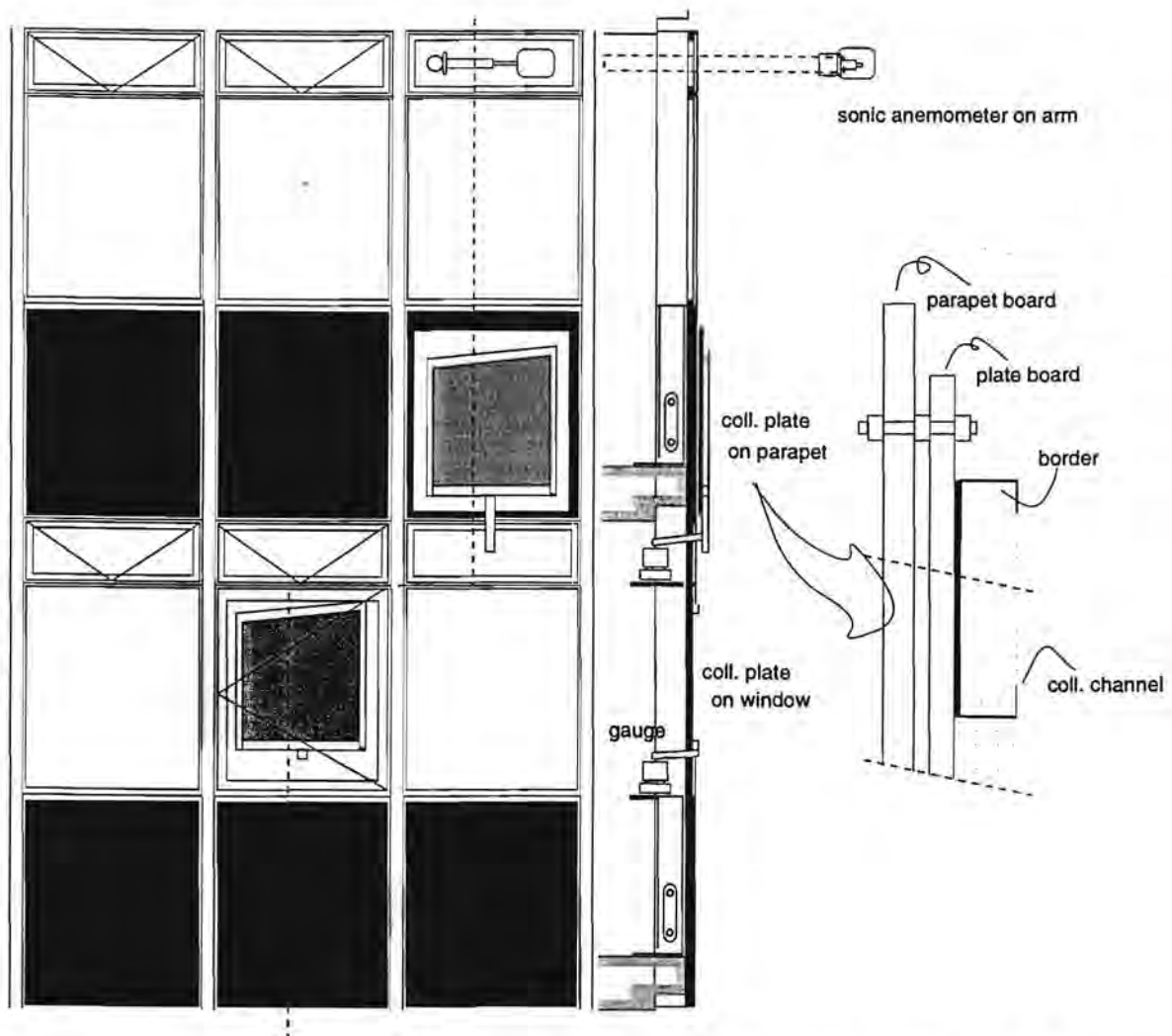 - registers them in 1 min-averaged format.

12

Figure 9: View from outside, section and details of the cladding of the Main Building. A d.r. gauge can either be fixed on a parapet, or on a board placed in a window.

— (if possible) measures and registers the drop spectrum on a location on the facade,
— switches back to slow operation mode, some time after the end of a rain event.
- The measurement system can relatively easy be extended to a full measurement of the micro-climatology of the facade of the main building of the TUE. For Geurt's research wind-induced pressures were measured [Geurts 1994]. Such measurements, together with driving rain, temperature, air humidity and sun irradiance, could provide a complete data set of the outdoor climate, which can be useful for calculations on e.g. moisture transport in walls, and for laboratory tests for facade elements.

If there is enough time, this will be tried to achive, although the investigations of the research presented here are limited to the measurement of rain and wind.

4.2 Problems and suggestions

The measurement set-up described in the above section is still a plan. Comments and suggestions on it are very welcome. Below two problems and suggestions are listed:
— One of the main problems is the location of the driving-rain gauges and the anemometer at the building facade. Also is is hard to give good points for the number of measuring locations. In general one is inclined to measure at as many locations as possible; but this is not practically nor financially possible.

Following two « rules » can yet be given: (1) for an overview of wetting pattern and building geometry the measurement locations should be oriented according to the symmetrics of the building envelope, (2) to have an idea on driving-rain intensity distributions one should try to pick out locations with very different intensities: edges and upper zones of the facade for the high driving-rain intensities and the middle zone for the lower intensities.

According to these two rules the locations depicted in figure 8, have been determined.

— In a later stage of the research (see section 1.2) is to compare measurements and computer calculations of driving rain on the main building. Very important for the right calculation of driving rain is the calculation of the wind pattern. What is the experience in this field? How is it possible to compare measurements and calculations, considering the full complexity?

Only a comparison in one concrete situation (i.e. one building and one weather type) is not enough to conclude in a general way on the applicability of c.f.d. for driving-rain assessments. In international circle this could be possible by measuring in different situations according to a certain standard method, and comparing the results of measurements and calculations.

Abreviations and symbols

Abreviations

c.f.d.	computational fluid dynamics
d.r.	driving rain on the building envelope
d.r.i.	driving-rain index ($[m^2\ s^{-1}]$, $= U_{met} \times R_{met\ hor}$)
free d.r.	free driving rain (i.e. in unobstructed wind flow)
hor.	horizontal (e.g. R_{hor} is the rain intensity through a horizontal plane)
ver.	vertical (e.g. R_{ver} is the rain intensity through a vertical plane)

Latin symbols

A	$[m^2]$	area
a	$[m]$	drop radius
M_A	$[kg\ m^{-2}\ s^{-1}]$	total mass flow through a plane per second ($=$ rain intensity)
m_A	$[kg\ m^{-2}\ s^{-1}]$	drop mass distribution through a plane per second
m_V	$[kg\ m^{-3}]$	volumetric drop mass distribution
N_A	$[m^{-2}\ s^{-1}]$	total number of drops through a plane per second
N_V	$[m^{-3}]$	total number per volumetric unit
n_A	$[m^{-2}\ s^{-1}]$	drop size distribution through a plane per second
n_V	$[m^{-3}]$	volumetric drop size distribution
Δp	$[Pa]$	pressure difference over the building envelope
R	$[mm/h]$	rain intensity ($R = 3600 \times M_A$)
t	$[s]$	time
U	$[m\ s^{-1}]$	windspeed vector
u	$[m\ s^{-1}]$	drop velocity vector
V	$[m^{-3}]$	volume
x	$[m]$	position

Greek symbols

α	$[s\ m^{-1}]$	free-d.r. factor, equal to $R_{free\ dr}/(U_{met}R_{hor})$
κ	$[-]$	catch ratio, equal to $R_{dr}/R_{free\ dr}$
ρ	$[kg\ m^{-3}]$	density

Super- and subscripts

$*$	normalized by dividing with the total number or total mass
met	measured at a local weather station, according to meteorological standards, for e.g. $U_{met} =$ windspeed at 10 m height in unsturbed flow

References

Basart, A. (1946). Verhandeling inzake de regenval op het verticale vlak met betrekking tot de bouw-constructie. Technical Report, Instituut voor warmte-economie TNO, Keramisch Instituut TNO.

BSI (1992). *BS 8104: Code of practice for assessing exposure of walls to wind-driven rain.* BSI.

Choi, E. (1993). Simulation of wind-driven-rain around a building. *Journal of Wind Engineering and Industrial Aerodynamics* **46/47**, 721–729.

Choi, E. (1994a). Characteristics of the co-occurrence of wind and rain and the driving-rain index. *Journal of Wind Engineering and Industrial Aerodynamics* **53**, 49–62.

Choi, E. (1994b). Determination of wind-driven-rain intensity on building faces. *Journal of Wind Engineering and Industrial Aerodynamics* **51**, 55–69.

Choi, E. (1994c). Parameters affecting the intensity of wind-driven rain on the front face of a building. *Journal of Wind Engineering and Industrial Aerodynamics* **53**, 1–17.

Choi, E. (1995, January). Numerical modelling of gust effect on wind-driven rain. In: *9th International Conference on Wind Engineering, New Delhi, India*, p. 214–215.

Fazio, P., S. Mallidi, and D. Zhu (1995). A qualitative study for the measurement of driving rain exposure in the Montréal Region. *Building and Environment* **30**(1), 1–11.

Frank, W. (1973). Einwirkung von regen und wind auf gebäudefassaden. In: *Berichte aus der Bauforschung*, Volume H. 86, p. 3–13. Berlin: Wilhelm Ernst & Sohn.

Gandemer, J. and G. Barnaud (1995, January). The Jules Verne climatic wind tunnel: innovative design for aerodynamic and climatic studies. In: *9th International Conference on Wind Engineering, New Delhi, India*, p. 1740–1741. International Association for Wind Engineering.

Geurts, C. (1994). Metingen op ware grootte van de windbelasting op gebouwen in een bebouwde omgeving. Voordracht op bko-research-dag, Technische Universiteit Eindhoven, vakgroep BKO.

Henriques, F. (1992). Quantification of wind-driven rain — an experimental approach, A general review on driven rain and details of an experiment in Portugal to supplement existing research results in Norway, the UK and elsewhere. *Building Research and Information* **20**(5), 295–297.

Hens, H. and F. A. Mohamed (1994). Preliminary results on driving rain estimation, t2-b-94/02. In: *Annex 24 (Heat, air and moisture transfer through new and retrofitted insulated envelope parts (Hamtie))*.

Joss, J. and A. Waldvogel (1967). Ein Spektrograph für Niederschlagstropfen mit automatischer Auswertung. *Pure and Applied Geophysics* **68**, 240–246.

Knollenberg, R. (1970, February). The optical array: An alternative to scattering or extinction for airborne particle size determination. *Journal of Applied Meteorology* **9**, 89–103.

Künzel, H. (1994a). Bestimmung der schlagregenbelastung von fassadenflächen. *IBP-Mitteilung* **21**(263).

Künzel, H. (1994b). Regendaten für die berechnung des feuchtetransports. *IBP-Mitteilung* **21**(265).

Lacy, R. (1965). Driving-rain maps and the onslaught of rain on buildings. In: *RILEM/CIB Symposium on Moisture in Buildings, Helsinki (SF)*.

Lacy, R. (1977). *Climate and building in Britain; A review of meteorological infomation suitable for use in the planning, design, construction and operation of buildings.* London: Building Research Establishment.

Matthews, R., M. Bury, and D. Redfearn (1996). Investigation of dynamic water penetration tests for curtain walling. *Journal of Wind Engineering and Industrial Aerodynamics* **60**, 1–16.

Middleton, W. K. (1969). *Invention of the meteorological instruments.* Baltimore: The Johns Hopkins Press.

Osmond, S. (1995, March). Assessment of the full scale micro-climate around buildings. Technical Report N47/95, Building Research Establishment.

Osmond, S. (1996, April). Assessment of the full scale micro-climate around builings. Technical Report N91/96, Building Research Establishment.

Prior, M. (1985). Directional driving rain indices for hte United Kingdom — computation and mapping. Background to BSI Draft for Development DD93. Building research establishment report.

Sankaran, R. and D. Paterson (1995). Computation of rain falling on a tall rectangular building. In: *9th International Conference on Wind Engineering, New Delhi, India*, p. 2127–2137. International Association for Wind Engineering.

Sankaran, R. and D. Peterson (1995, January). Wind driven rain: data collection facility at CSIRO, Sydney, Australia. In: *9th International Conference on Wind Engineering, New Delhi, India*, p. 2023–2033. International Association for Wind Engineering.

Schönhuber, M., H. Urban, J. P. Baptista, W. Randeu, and W. Rielder (1994, November). Measurements of precipitation characteristics by a new disdrometer. In: *Proceedings of Atmospheric Physics and Dynamics in the Analysis ad Prognosis of Precipitation Fieds, Rome (IT)*.

Schwarz, B. (1973). Die Schlagregenbeanspruchung von Gebaäden, Meßmethoden — Meßgeräte. In: *Berichte aus der Bauforschung*, Volume H. 86, p. 3–13. Berlin: Wilhelm Ernst & Sohn.

Sheppard, B. (1990a, February). Effect of irregularities in the diameter classification of raindrops by the Joss-Waldvogel disdrometer. *Journal of Atmospheric and Oceanic Technology* **7**, 180–183.

Sheppard, B. (1990b, April). Measurement of raindrop size distributions using a small Doppler radar. *Journal of Atmospheric and Oceanic Technology* **7**, 255–268.

Sheppard, B. and P. Joe (1994, August). Comparison of raindrop size distribution measurements by a Joss-Waldvogel disdrometer, a PMS 2DG spectrometer, and a POSS Doppler radar. *Journal of Atmospheric and Oceanic Technology* **11**, 874–887.

Surry, D., D. Inculet, P. Skerlj, J.-X. Lin, and A. Davenport (1994). Wind, rain and the building envelope: a status report of ongoing research at the University of Western Ontario. *Journal of Wind Engineering and Industrial Aerodynamics* **53**, 19–36.

Wang, T. (1982, January). Near-field laser disdrometer for raindrops. *Applied Optics* **21**(1), 11–12.

Wang, T., K. Earnshaw, and R. Lawrence (1978, February). Simplified optical path-averaged rain gauge. *Applied Optics* **17**(3), 384–390.

Wessels, H. (1967, January). Druppelgroottemeter voor regen. Verslag v 197-vi, KNMI, De Bilt.

Winkler, P. (1993, February). Principles of automatic rain detection. *Meteorol. Zeitschrift* **N.F. 2**, 27–34.

Zhu, D., S. Mallidi, and P. Fazio (1995). Approach for urban driving rain index by using climatological data recorded at suburban meteorological station. *Building and Environment* **30**(2), 229–236.