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Stochastic simulation of rain intrusion through small defects due to water rivulet overpressure. Introducing a driving rain leakage potential.

C.-E. Hagentoft[,1]**, L. Olsson**[2]

[1] Chalmers University of Technology
[2] RISE Research Institutes of Sweden

carl-eric.hagentoft@chalmers.se

Abstract. There is a need of upgrading the old building stock with respect to the thermal insulation of the building envelope and specifically the façades. There are several systems on the market, and some are quite new and innovative. To bring down the cost some of the systems many are based on prefabricated moisture tight insulated units. This means that in case there is moisture tight barrier on the interior side, two moisture tight barriers surround the wall structure. The leakage of driving rain into the structure then represents a major threat to the durability of these systems. This paper investigates the pressure build up in water rivulets running down a façade acting together with the wind pressure. A driving rain leakage potential is introduced. Using real weather data years and Monte Carlo Simulations, the mean and standard deviation of the annual leakage through small hole is estimated. The examples show that the leakage can reach a level 0-0.5 liter/year for a hole with a diameter of 1-2 mm, and 0.5-3 liter/year for a diameter of 3-4 mm.

1. Background

One of the main functions of the exterior walls is to separate and protect the indoor from the outdoor climate to provide an energy efficient building with good indoor environment (thermal comfort, shading from sun and rain etc.). However, water can leak into outer walls and façades [2,6,7,9,11] to a greater or lesser degree, even in pressure-equalized façades [8,12]. Newly results from field and laboratory measurements in Sweden confirm the statement that façades are usually not watertight according to ASHRAE standard 160 [9,13].

Further, the risk of rain intrusion is greater in the presence of façade details than in an unimpaired wall since inward leakage often occurs in correspondence to the joints around façade details. Joints around window-wall interfaces are one of the most common façade details, and windows often make up a relatively large proportion of the façade area. For this reason, although the façade material itself is impervious to rain, the wall itself may still be damaged due to leaks around façade details [13]. Research in this area has newly been performed to offer more data and to quantify and understand the amount of leakages [10] basically to design and assess new and existing solutions, in a reliable manner. Further, there is a need of upgrading the old building stock with respect to the thermal insulation of the building envelope and specifically the façades. There are several systems on the market, and some are quite new and innovative. To bring down the cost some of the systems are based on prefabricated moisture tight insulated units. This means that in case there is moisture tight barrier on the interior side, two moisture

tight barriers surround the wall structure. The leakage of driving rain into the structure then represents a major threat to the durability of these systems.

Overall, there is currently a lack of reliable theoretical analytic tools capable of fully planning and assessing the risk to an external wall's moisture control capabilities when façade details are present [1]. Assumptions are often used, based on a given percentage of driving rain that penetrates [13], distributed per square meter. But, however, there are usually point leakages [8] in façades and the spread of water within the wall is usually unknown. This is an important factor we need to be aware of in the moisture safety assessment. The purpose of this article is to take a further step in modelling rain intrusion. The intention is to introduce a simplified driving rain leakage potential, based on stochastic simulation, that can be used for an initial assessment of the leakage.

2. Driving rain and formation of rivulets

Depending on how wet the façade surface is and the intensity of the driving rain the rainwater can stay or start to run downwards the facade. There are two basic alternative modes for the runoff. The water can flow in a film with a given thickness or in a few rivulets. Figure 1, left illustrates the problem to be addressed. Straight rivulets are assumed for simplicity. In reality, they are meandering down along the façade, see Figure 1, right. The unit area of interest is located at the distance H (m) from the upper edge of rain collecting surface. The driving rain intensity is g_{DR}^{*} (kg/(m²s)).
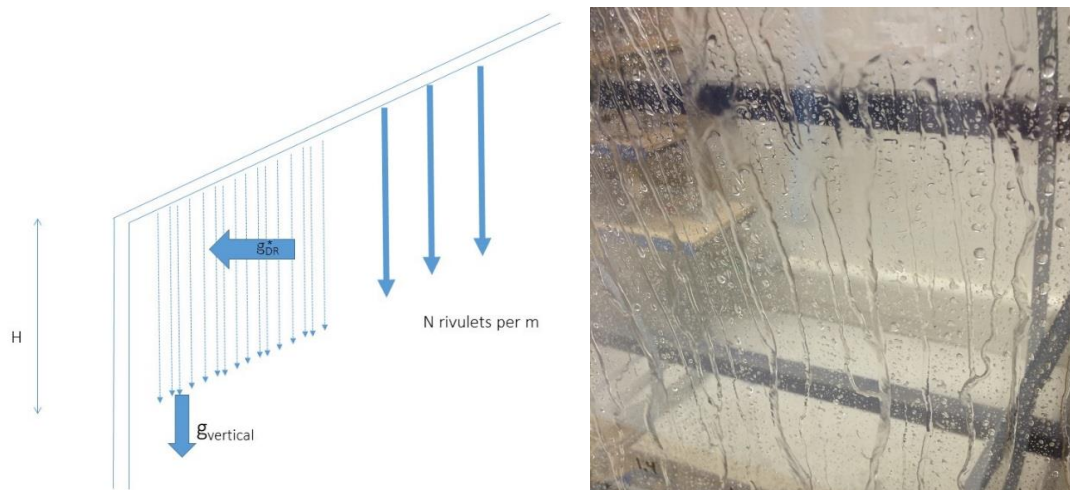
Figure 1. Rainwater runoff on a surface. To the left: principle definitions. To the right: photo from an experiment with rivulets on a glass surface.

If all water flows along the surface, the intensity, $g_{vertical}$ (kg/(ms)) is:

$$g_{vertical} = g_{DR}^{*} \cdot H \tag{1}$$

For the case of rainwater flowing down in N rivulets per meter façade (horizontally) the following flow, G_{riv} (kg/s per rivulet), in each rivulet becomes:

$$G_{riv} = \frac{g_{vertical}}{N} \tag{2}$$

The shape of the rivulet, assuming a constant width, w (m) is shown in Figure 2.

Figure 2. Left: Water flowing in a single rivulet. Right: Contact angle θ_{riv} of the rivulet.

3. Driving forces

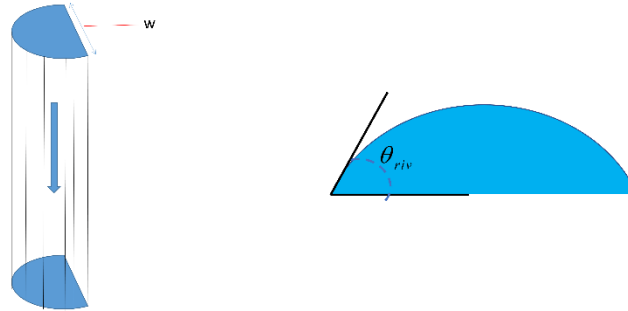The pressure difference over a hole in a façade element determines the leakage of water. The air pressure difference P_a (Pa), which depends on the success of the pressure equalization of the façade element, is of importance. Depending on the geometry of the building and the design of the façade, we can assume the following air pressure difference over the façade element:

$$P_a = f \cdot \frac{\rho_{air} v^2}{2} \tag{3}$$

Here, v is the wind speed at the site of the building and f is a non-dimensional factor. The factor must be determined based on the actual situation. For simplicity the value 0.5 is used below. The density of air is ρ_{air} (kg/m³). On the wind ward side, its value is approximately between zero and one.

The pressure build-up in the rivulet with a contact angle of θ_{riv} is [3]:

$$P_{riv} = \frac{\gamma \cdot \sin(\theta_{riv}) \cdot 2}{1 \cdot w} = \frac{2\gamma \cdot \sin(\theta_{riv})}{w} \tag{4}$$

The surface tension coefficient, γ, for water at 20 °C is equal to 72,8 mN/m. The relation between the flow rate and width, [3], is:

$$w = 2 \cdot \left(\frac{105 \cdot \mu \cdot G_{riv} / \rho}{4 \rho g \cdot \tan^3 (\theta_{riv})} \right)^{1/4} \tag{5}$$

Here, ρ (kg/m³) is the density of water and μ is the dynamic viscosity of water (approximately 0.001 kg/m/s, at 20 °C). The relation between the flow rate and pressure [4], is:

$$P_{riv} = \gamma \cdot \left(\frac{4\rho^2 g}{105 \cdot \mu} \right)^{1/4} \cdot \sin(\theta_{riv}) \cdot \tan^{3/4}(\theta_{riv}) \frac{1}{G_{riv}^{1/4}} \tag{6}$$

Water height differences, h (m), across the hole in the façade causes hydrostatic pressure. This can act as a driving force that will increase the leakage as well as a counter acting force depending on the slope of the hole. Together with the pressure due to a developed water meniscus at the interior side of the hole, a barrier pressure can be defined [4]:

$$P_B = \frac{4\gamma \cdot \sin(\theta)}{D_c} - h\rho g \tag{7}$$

Here, θ, is the contact angle of the water meniscus with the substrate on the back side of the façade material. The first term represents a pressure of approximately 206 Pa, 103 Pa, 69 Pa, 51 and 26 Pa for a contact angle of 45° and a diameter D_c of 0.001 m, 0.002 m, 0.003 m, 0.004 m and 0.008 m respectively. For a slope upwards, h=-0.001 m, the second term represents a pressure of approximately 9.8 Pa.

4. Potential for leakages

The total pressure, ΔP (Pa), acting over the small hole becomes:

$$\Delta P = P_a + P_{riv} - P_B \tag{8}$$

As long as the total pressure is not exceeding 0 Pascal there will be no flow through the hole. Once the pressure is higher than zero, the barrier meniscus will burst and disappear, and water will flow out on the backside of the façade material. Assuming laminar flow inside the tube, neglecting inlet and outlet pressure losses, the flow G_{in} (kg/s) becomes:

$$G_{in} = \frac{P_a + P_{riv}}{R_p} \tag{9}$$

The flow resistance R_p (Pa·s/kg) for a hole with the diameter D_c (m) and a length L_c (m) is estimated to:

$$R_p = \frac{16 \cdot 8 \mu L_c}{\pi \rho D_c^4} \tag{10}$$

The total water leakage M (kg) through the hole during a year, with the formation of N (-) rivulets per meter wall, becomes:

$$M = \int_0^{t_{year}} H_{st}\left(driving\ rain, \Delta P\right) \frac{P_a + P_{riv}(w(N))}{R_p} P\left(hit\right) dt \tag{11}$$

The notation H_{st}, (-) refers to a function that has the value 1 when driving rain over a certain intensity is hitting the façade and the total driving pressure, ΔP, exceeds zero, otherwise it is zero The notation, $P\ (hit)$, represents the likelihood, between 0 and 1, for any of the rivulets to hit the hole. The likelihood of one single rivulet to hit a hole is D_c (i.e. the hole width per meter. For at least one rivulet to hit is then approximately equal to $1 - (1 - D_c)^N$. Here, the dependence of the rivulet width is neglected. The *Driving rain leakage potential* is introduced, W (Pa h).

$$M = \frac{W}{R_p} \qquad W = \int_0^{t_{year}} H_{st}\left(driving\ rain, \Delta P\right) \cdot \left(P_a + P_{riv}(w(N))\right) \cdot P\left(hit\right) dt \tag{12}$$

This formula for the leakage assumes that only one rivulet is hitting the hole per time unit and that water is available that matches the flow calculated by (9). This is not always the case and (14) will estimate the upper limit. This will for instance happen for small rivulets with a very high pressure but with an actual low flow rate. Furthermore, runoff is always assumed to occur as soon as driving rain exceeds a certain threshold intensity is hitting the façade. The total time that water leakage occurs becomes:

$$t_{leakage} = \int_0^{t_{year}} H_{st}\left(driving\ rain, \Delta P\right) \cdot P\left(hit\right) dt \tag{13}$$

The maximum leakage through the hole, the upper limit of (12), is determined by the flow in a single rivulet that is hitting it:

$$M_{max} = \int_0^{t_{year}} H_{st}\left(driving\ rain, \Delta P\right) \cdot G_{riv} \cdot P\left(hit\right) dt \tag{14}$$

5. Simulation results

Weather data (hourly data) representative for Gothenburg (1961-2000) have been used. The driving rain intensities have been calculated using classical Lacy estimations based on wind transformations to the height of the hole [5]. The position of the leakage hole is at the height of 3 m from the ground on a façade surface facing south west, the orientation locally with most exposure to driving rain. The rain collecting area height H is 3 m. The average yearly precipitation in Gothenburg is around 900 mm with a standard deviation of approximately 100 mm.

For each rainy hour of the year the number of rivulets N is calculated based on a rectangular distribution of whole numbers between 1 and N_{max}. The hourly driving rain threshold intensity is 0.05 mm/h. Below this value run off is neglected. The hydrostatic pressure part in (7) is neglected, i.e. $h=0$.

Using the Monte Carlo method for a repeated number of randomly chosen years, the mean and the standard deviation of the driving rain leakage potential is calculated for different values of D_c and P_B. In total 8000 randomly chosen years from a set of 40 have been used in the simulation. A histogram for one example is shown in Figure 3. Convergence has been tested by comparing with simulations using 4000 years. Differences are minor and found in the 3rd digit. Figure 3 shows the histogram for the driving rain leakage potential for the case of $f=0.5$, $N_{max} = 10$, contact angles $\theta_{riv} = 45°$, and $P_{B=}$ 51 Pa ($D_c =4$ mm, $\theta = 45°$). Tables 1-2 show the calculated driving rain leakage potential for $f=0.5$, $N_{max} =5$ and 10, contact angles $\theta_{riv} = 45°$, and $P_{B=}$206 Pa, 103 Pa, 69 Pa, 51 Pa and 26 Pa, representing $D_c =1$, 2, 3, 4 and 8 mm. The corresponding cases with contact angle of $\theta_{riv} =10°$ results in zero driving rain potential, except for the case of $D_c =0.008$ m / $P_B =26$ Pa which results in negligible values.

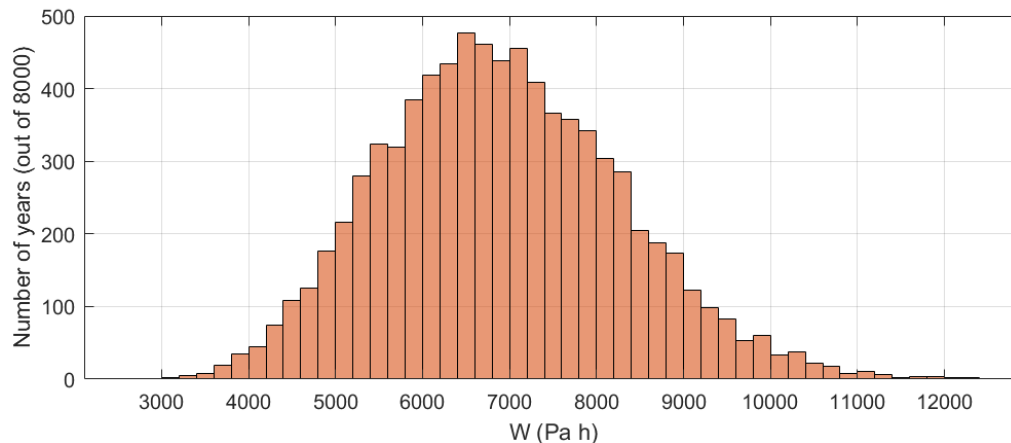**Figure 3.** Histogram for the driving rain leakage potential, W (Pa,h). f is equal to 0.5, $N_{max}=10$ and the contact angle of θ_{riv} equal to 45°, $D_c =0.004$ m, $P_B=51$ Pa.

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Table 1. The mean value and standard deviation for the driving rain leakage potential, W (kPa,h). Contact angle θ_{riv} is equal to 45° and $N_{max}=5$. The hole diameter D_c and the corresponding barrier pressure P_B for contact angle of 45° is varied.

D_c (mm) / P_B (Pa)	1 /206	2/103	3/69	4/51	8/26
$\bar{W} / \sigma_W$ (kPah)	0.067/0.121	1.3/0.47	2.4/0.66	3.2/0.78	6.4/1.2
$\bar{M} / \sigma_M$ (kg/year)	≈0/≈0	0.050/0.019	0.47/0.13	2.0/0.49	64/12

$\bar{M}_{max} / \sigma_{M_{max}}$ (kg/year)	0.0049/0.0039	0.26/0.11	1.6/0.65	2.9/1.2	5.8/2.1
$\bar{t}_{leakage}$ (h)	0.31	8.4	18	25	50

Table 2. The mean value and standard deviation for the driving rain leakage potential, W (kPa,h). Contact angle θ_{riv} is equal to 45° and N_{max}=10. The hole diameter D_c and the corresponding barrier pressure P_B for contact angle of 45° is varied.

D_c (mm) / P_B (Pa)	1 /206	2/103	3/69	4/51	8/26
$\bar{W} / \sigma_W$ (kPah)	0.44/0.33	3.1/0.81	5.2/1.1	6.9/1.4	14/2.2
$\bar{M} / \sigma_M$ (kg/year)	$\approx 0/\approx 0$	0.12/0.032	1.0/0.22	4.3/0.85	140/22
$\bar{M}_{max} / \sigma_{M_{max}}$ (kg/year)	0.011/0.0057	0.47/0.16	1.9/0.68	2.8/1.05	5.7/1.8
$\bar{t}_{leakage}$ (h)	1.9	19	34	46	90

For the cases in Table 1, N_{max}=5, the calculated leakage, M, will exceed the maximum one, M_{max}, for diameters D_c greater than approximately 4 mm. For these bigger holes the maximum number should be used for leakage estimates. For the cases in Table 2, N_{max}=10 this threshold is reached at D_c greater than approximately 3 mm. The hours of leakages range up to 90 hours, i.e. approximately 4 days. The leakage time is greater, approximately the double, for 10 instead of 5 rivulets.

The maximum leakage $\bar{M}_{max}$ reaches the same level for the big holes (4 and 8 mm) and is proportional to the hole diameter. This is consistence with what could be expected if the runoff would be of a uniform film instead of in rivulets. For these bigger holes the pressure barrier effect is also minor.

Tables 3-4 show the calculated driving rain leakage potential and leakages for the case of a barrier pressure P_B equal to 0 Pa ($\theta = 0°$). The results differ mainly for smaller holes (1-2 mm) compared to the cases in Table 1-2.

Table 3. The mean value and standard deviation for the driving rain leakage potential, W (kPa,h). Contact angle θ_{riv} is equal to 45° and N_{max}=5. The hole diameter D_c is varied and the barrier pressure P_B is 0 Pa ($\theta = 0°$).

D_c (mm)	1	2	3	4	8
$\bar{W}/\sigma_W$ (kPah)	0.81/0.35	1.6/0.52	2.4/0.66	3.2/0.78	6.4/1.2
$\bar{M}/\sigma_M$ (kg/year)	$\approx$0/$\approx$0	0.063/0.020	0.48/0.13	2.0/0.49	64/12
$\bar{M}_{max}/\sigma_{M_{max}}$ (kg/year)	0.74/0.62	1.5/0.90	2.2/1.1	2.9/1.3	5.7/2.1
$\bar{t}_{leakage}$ (h)	6.3	13	19	25	50

Table 4. The mean value and standard deviation for the driving rain leakage potential, W (kPa,h). Contact angle θ_{riv} is equal to 45° and N_{max}=10. The hole diameter D_c is varied and the barrier pressure P_B is 0 Pa ($\theta = 0°$).

D_c (mm)	1	2	3	4	8
$\bar{W}/\sigma_W$ (kPah)	1.7/0.58	3.5/0.86	5.2/1.1	6.9/1.3	14/2.2
$\bar{M}/\sigma_M$ (kg/year)	$\approx$0/$\approx$0	0.14/0.034	1.0/0.22	4.3/0.85	140/22
$\bar{M}_{max}/\sigma_{M_{max}}$ (kg/year)	0.72/0.48	1.5/0.72	2.2/0.91	2.9/1.1	5.7/1.8
$\bar{t}_{leakage}$ (h)	11	23	34	46	90

6. Discussion

There are a lot of factors that must be taken into account when calculating rainwater leakage. The process is stochastic, originating both from the weather itself as well as the intricate physics of water trickling down the façade surface. Experiments show [10] that point-wise water leakage with holes of a diameter 1-8 mm, similar the ones considered here with pulsating wind pressure of up to 600 Pa, is in the range of 0.5-2% of the run off per meter wall horizontally, here denoted by $g_{vertical}$. This wind pressure is used for testing purposes and is higher than what is found in the simulated cases. In this article the runoff corresponds to an average of 729 liter/m/year and a standard deviation of 160 liter/m/year. The mean leakage according to this rule of thumb would then be in the range of 3.6-14.6 liter /m/year. The numbers found is this article is in line with the lower range of this interval. The higher numbers in [10] is justified by the higher wind pressure and the hydrostatic positive pressure buildup accounted for.

Accounting for a barrier pressure due to the slope and the pressure of the water meniscus on the backside of the cladding reduces the leakage rate and can be omitted in a more conservative estimation. Both the slope due to the height h (m) and if in fact the meniscus is forming is difficult to determine.

7. Conclusions

The presented simulation model is based on deterministic expressions derived from physics involving the pressure from wind and surface tension. The model accounts for the wind driven rain and the contact angle of water for the façade surface material. A driving rain leakage potential is introduced that can be used in the comparison of different climates, the building orientation and surface material. By using the potential and the geometry of the hole, the rain leakage can be estimated.

A greater contact angle of the rivulets is increasing the leakage as well as the development of a greater number of rivulets.

For holes greater than 3-4 mm the leakage can be estimated directly from the water flow in the rivulets that hits the hole. The examples show that the leakage can reach a level 0-0.5 liter/year for a hole with a diameter of 1-2 mm, and 0.5-3 liter/year for a diameter of 3-4 mm. The hours of leakages are in the range of 1 hour for 1mm holes and 90 hours for 8 mm holes.

The leakage time seems to be proportional to the assumed number of rivulets. For small holes, 1-3 mm, the leakage rate, and the leakage time is greater when assuming that more rivulets are formed. The likelihood for any one of the rivulets to hit the hole increases with the rivulet number. Also, the rivulet pressure is higher for smaller width which is a direct consequence of higher number of rivulets.

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