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New algorithm for water leakages flow through rain screen deficiencies

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ABSTRACT
There is a need of more knowledge about the mechanisms of water leakage through façades exposed to driving rain to make reliable risk analyses. Therefore, we have studied it in more detail and the outcome include inter alia a new algorithm. The algorithm is developed for calculation of water leakages through rain screen deficiencies. The algorithm is based on empirical values from many measurements according to standardized test method and validation. Even though the leakage process is very complicated, simple correlations have been shown. The leakages flow rate through deficiencies are mainly limited by the runoff rate and the catch area above the hole and around the hole with dam. Apart from wind pressure as a driving force, the inlet of the holes is often on a higher level than the outlet at the rear of the façade, which creates significant hydrostatic pressure, which can be elevated by impoundment at the obstacle. This is the main reasons to comprehensive water leakages through façades without any wind pressure (pressure equalized façades).
If precise information about defects data is not available, there are extensive measurements supporting the following assumption – a realistic leakage flow for a small or invisible spot leakage at a façade detail is presumed to be 0.5 to 2% of the runoff rate per meter of façade width. If there are multiple penetrations or obvious defects in the façade design in combination with the dams, a significantly higher proportion of the runoff flow can leak in.

KEYWORDS
Rain intrusion, runoff, catch area, mechanisms of water leakage, façade details

INTRODUCTION
The latest research in Sweden confirms the statements in ASHRAE Standard 160, which state that façades are normally not completely rainproof (ASHRAE, 2016) and should be considered in moisture calculations (Olsson, 2017b). In addition, there is no reliable theoretical risk analysis tool to assess the moisture resistance of new façade solutions and of renovation solutions (Bednar & Hagentoft, 2015). If you rely solely on today's theoretical analyses, you end up underestimating water intrusion with consequences such as moisture-related damage, interior environment problems, and failure to meet energy efficiency requirements. Among other things, there is a lack of input data for driving rain intrusion to enable sufficiently relevant analyses. Several studies have therefore been conducted in recent years to investigate rain resistance due to driving rain and leakage flow in full scale with different solutions and different mounted details in Sweden (Olsson, 2017a).

One significant conclusion from the studies is that leakage at cracks and joints between façades and façade details and details are more the rule than the exception, regardless of façade type, material, ventilated vs unventilated, etc. Similar conclusions are drawn in other similar studies (Lacasse, 2003, Straube, 1998). Furthermore, (Olsson, 2016) has shown that significant leakage can be expected even in extremely small and invisible penetrations,

making it difficult or practically impossible to visually assess whether attachment details have been mounted tight. It is a matter of spot leakage flows of 0.01–0.05 l/min,m during a heavy driving rain load for rain-exposed multi story façades or 0.5–2% of the runoff rate per meter of façade width (Olsson, 2017a) for small or invisible penetrations. These results correlate well with an earlier study (Sahal & Lacasse, 2004), where a function was developed to describe the connection between applied quantity and leakage flow. The percentage of leakage in the study was 1.2–2.5% of the runoff rate per meter of façade width. It penetrated via a 50 mm elastic joint that was missing sealant between a mounting plate and the façade (in connection to a ventilation lead-through in the façade with a 15 mm protrusion). A study of a field experiment that was published relatively recently (Ngudjiharto, 2015) showed that the percentage of leakage flow was 1.5% of the runoff rate at a window detail with a 90 mm long penetration (without dam). Naturally, greater leakage can occur with noticeable penetrations, multiple penetrations in close proximity, façade details that both dam and lead in water, and extreme loads (Van Den Bossche, 2013, Lacasse, 2003).

The outcome of several of these studies and a newly study, (Olsson & Hagentoft, 2018) to be submitted 2018, which this paper is mainly based on has increased the understanding, both practical and theoretical, of driving rain intrusion and its mechanisms, and to present a modelling theory.

METHODS
Many targeted experiments with different vertical surfaces (fibre cement and polycarbonate board) and different hole geometry and dam sizes were conducted. The results of the measurement and linear regression analysis serve as the basis for the empirically-determined values. As in previous studies (Olsson, 2017a), a standardized method, EN 12865, (SIS, 2001) was used. Additionally, theory from literature and simple phenomenological experiments performed prior served as the basis for describing the water's behaviour on a vertical surface and with different types of defects.

THEORY
A theoretical description of the most dominated factors and forces involved that are of practical significance to the inward leakage process follows.

Amount of water that can reach the defect
If the façade is capillary saturated or non-moisture-absorbing, then all the driving rain that lands on the façade surface will run downwards and be added along the vertical façade surface. The greatest runoff rate thus occurs at the bottom of the façade provided there are no water-diverting details. The water quantity that loads a penetration, G_{max} (kg/s), is based on the area (catch area) above the penetration, defined by height, H, (m) and width, D or W, (m), see equation (1) and Figure 1(a). The width of the catch area is made up of either the width of the hole (D) or the width of the dam (W). The dam can direct in more water from surfaces next to and above the hole. Designations for the geometry of the dam are also provided in Figure 1(a) and (b). The driving rain intensity is denoted g_{DR} (kg/(m^{2}s))

$$G_{max} = H \cdot D \cdot g_{DR} \quad or \quad H \cdot W \cdot g_{DR} \tag{1}$$

The water leakage rate through the defect is denoted G (kg/s). We define a factor η (-) describing how efficiently the caught water is actually leaking in through the façade layer, see equation (2).
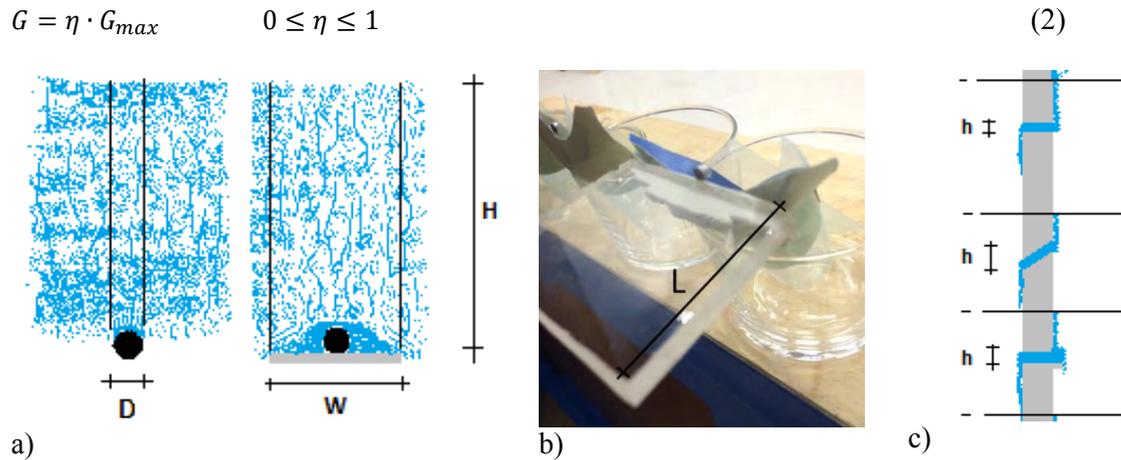
$$G = \eta \cdot G_{max} \qquad 0 \leq \eta \leq 1 \tag{2}$$

a)   b)   c)

Figure 1. (a) Catch area as regards hole width (D) or dam width (W) plus façade height (H). The assumed catch area is shown within the two vertical lines. (b) The figure shows a dam located at the bottom edge of a hole in a polycarbonate board. The dimension of the protrusion is given by (L). (c) Wall section with spraying water with different holes and a dam. The height difference (h) between the highest and the lowest point of the water across the hole constitutes the hydrostatic pressure. The figure shows how the water penetrates through a horizontal hole, downward-sloping hole and a hole with underlying dam.

Hydrostatic pressure

The hydrostatic pressure P_h (Pa) is determined by water depth h (m), gravity g (m/s^2) and the water's density ρ (kg/m^3); see equation (3) and Figure 1 (c). The highest pressure thus occurs at the bottom of a pool of water or at the bottom edge of a hole filled with water. Increased hydrostatic pressure may therefore occur at protruding details in façades that cause dams.

$$P_h = \rho \cdot g \cdot h \tag{3}$$

Wind pressure

In addition to the hydrostatic pressure described earlier, wind pressure is an essential driver for water leakage into façades due to air pressure difference across the façade layer. Assuming that the façade constitutes the dominant air pressure differences across the wall, the façade is subjected to the current wind pressure. The wind pressure P_w (Pa) across the façade layer can be estimated using the following formula, where wind velocity is denoted v (m/s) and f (-) is a form factor with a value somewhere between 0 and 1 depending primarily on wind direction in relation to the façade:

$$P_w = f \cdot \frac{\rho \cdot v^2}{2} \tag{4}$$

Capillarity and surface tension

The surface properties of the materials have a bearing on how water acts on material surfaces. Even if the material is not capillary absorbing, the water may act differently on a surface depending on the surface energy of the material, or as it is also called the surface tension. Water has a lower surface tension than e.g. hydrophilic materials like steel, aluminium, glass and stone. For this reason, the water tends to flow out over such material surfaces (De Gennes et al., 2004). Conversely, water has a higher surface tension than hydrophobic materials, such as many plastics. The water surface tension coefficient is denoted γ, for water at 20 °C is

equal to 72,8 mN/m. The meniscus that is formed on the backside of the rain screen is resulting in a counteracting pressure, with a radius r (m) and contact angle θ we get:

$$P_{men} = \frac{2\pi \cdot r \cdot \gamma}{\pi \cdot r^2} = \frac{2\gamma}{r} \tag{5}$$

MODEL

We assume that the total pressure will be an important factor to include in an algorithm for estimated leakage flow. Thus, the estimated value of the leakage factor can be expressed as:

$$\eta_{est} = f(P_{tot}) \tag{6}$$

The total pressure for a non-absorbing surface is obtained through:

$$P_{tot} = P_w + P_h - P_{men} \tag{7}$$

The counterpressure in the meniscus that forms on the rear counteracts leakage, while the pressure from the water column and the wind helps to increase the leakage. For an absorbing surface, a counteracting meniscus does not form on the rear in the same systematic way and P_{men} is set to zero otherwise given by (5).

VALIDATION OF MODEL

The measured leakage flow was examined in relation to the hole width or dam width and the actual runoff rate as per equation (2). We found that the dam width has a significant impact. If the hole is small in relation to the dam, maximal leakage efficiency of $\eta=0.5$ is obtained as a rough target value. The maximal leakage efficiency of $\eta=1$ is obtained at higher wind pressure as a rough target value.

The following formula, with linear relation to the total pressure, for leakage factor η_{est} was adopted:

$$\eta_{est} = \eta_0 + \alpha \cdot P_{tot} + \beta \cdot \frac{D}{W} + \gamma \cdot \frac{D}{L} \tag{8}$$

A large number of measurements were performed (Olsson&Hagentoft to be submitted 2018) and the constants in equation (8) were determined using linear regression, see Table 1. The wind pressure used in equation (4) relates to the maximum pressure that occurs under each wind pressure cycle. According to method EN 12865, the wind pressure during one-third of each cycle is zero, $P_w/2$ and P_w respectively. The average pressure over the cycle is thus $P_w/2$. The total pressure P_{tot}, used in equation (8) is set to zero if negative. η_{est} is limited to stay in the range of zero to one.

Table 1. Constants determined for equation (8) for a number of experimental cases. R^2 is a determination coefficient. The table applies for different runoff rates see column Runoff and different D width, see column Case.

Case	η_0	α	β	γ	R^2	Runoff (l/min,m)
Fiber cem. with hole (2/4/8 mm)	0.19	0.0011	-	-	0.71	2.9
(-//-)	0.16	0.0010	-	-	0.69	1.1
Fiber cem.-hole with dam (1/4 mm)	-0.039	0.00035	1.36	-0.044	0.85	2.9
(-//-)	0.012	0.00044	0.92	-0.055	0.71	1.1
Polycarbonate with hole (4 mm)	0.065	0.0013	-	-	0.88	2.9
(-//-)	0.19	0.0014	-	-	0.36	1.1
Polycarb. hole with dam (1/4 mm)	-0.011	0.00054	1.30	0.040	0.73	2.9
(-//-)	0.029	0.00042	0.77	-0.043	0.47	1.1

Comments for validation
The results of linear regression in Table 1 show in most cases $R^2 > 0.7$, which indicates that there are more or less clear correlations even though the water forms stochastically on surfaces to varying degrees. In some cases with low runoff rate, rivulets or small hole equal to 1 mm, there were no clear correlations for holes without dam.
We can establish that constants was not changed very much with different runoff rates, see Table 1. This indicates that the algorithm is applicable for different runoff rates with moisture-absorbing façades. Accordingly, equation (8) suits this best as a uniform water film is formed on the façade surface, resulting in a smaller spread in the repeated experiments. For non-absorbing materials, rivulets instead occur, particularly at low runoff rates, which move more stochastically across the surface.

USE OF ALGORITHM – AN EXAMPLE
An example of how the algorithm, equation (2), can be used is presented here. The driving rain load in, for example, Gothenburg for the most exposed compass direction is assumed to be 250 liters/year, m^2. For a pressure-equalized façade with a three-meter high façade (capillary saturated), the runoff rate that can strike a hole in the lower part of the façade is 750 liters/year,m. For a small, downward-sloping (h=60 mm) hole with e.g. a 3 mm diameter and with a dam of 60 mm (W) and 30 mm (L), (η_{est} = 0.24) as per equation (8) based on the constants for fibercement board (holes with dam) indicates a spot leakage of 11 liters/year (equivalent to 1.5% of the total runoff rate per meter of façade width), which is significant.

DISCUSSION AND COMMENTS
The algorithm was based on our own newly made studies and validated against measurement results from our own earlier studies and the studies of others (Olsson & Hagentoft, 2018), and seems to fall relatively well in line.

If precise data is not available, there are extensive measurements supporting the following assumption – a realistic leakage flow for a small or invisible spot leakage at a façade detail is presumed to be up to a few percent of the flow rate per meter of façade width. If there are multiple penetrations or obvious defects in the façade design in combination with the dams, a significantly higher proportion of the runoff rate can leak in. Exactly how the spread of the leakage in the wall appears, needs to be known or investigated, alternatively that the worst case scenario (the whole leakage is placed concentrated and in the most critical point) is applied.

CONCLUSION

A new calculation algorithm, using equation (2) and (8) was developed as an expression based on runoff rates that strike the width of the hole or dam, plus a factor η_{est}. The constants in equation (8) are based on empirical values. The new knowledge increases the ability to make more accurate calculations of expected leakage flows. However, there must be exact data on factors such as geometry and the dimensions of holes and dams. Furthermore, the constants in Table 1 must be selected with respect to representative of the façade material.

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