Implementation of rainwater infiltration measurements in hygrothermal modelling of non-insulated brick cavity walls

Klaas Calle, Charlotte Coupillie, Arnold Janssens and Nathan Van Den Bossche

Abstract
The watertightness of solid masonry walls is generally based on the concept of buffering and afterwards drying out the absorbed rainwater. In cavity walls, on the contrary, the air layer provides a capillary break between the inner and outer leafs allowing drainage of rainwater and preventing infiltration to the interior wall surface. For assessing moisture-related risks, heat, air and moisture models have proven to be a valuable tool, but in the case of cavity walls two problems arise: the degree of water infiltration into the cavity is unknown, and no consensus is available on the method that should be used to implement these infiltrations in a simulation. For example, for the existing buildings, it is worthwhile to investigate whether injecting cavity wall insulation induces an increase or decrease in moisture-related pathologies, in contrast to adopting a fixed performance criterion for assessment. However, to complete a thorough analysis of a brick cavity wall, it is first useful to review the hygrothermal behaviour of cavity walls as it has been previously described in the literature. As such, this article provides a summary of experimental water infiltration results for cavity walls as described in the literature, discusses experimental results of four test walls subjected to four test protocols and extracts from these results the water infiltration rate for implementation in heat, air and

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moisture models. Finally, several methods for implementing the infiltrations in heat, air and moisture simulations are presented and evaluated based on different damage criteria. In general, the new modelling approaches are considered to provide realistic results. Nonetheless, in situ investigation on whether mortar bridges occur in the cavity due to poor workmanship remains crucial to understanding the hygrothermal response as mortar bridges are found to have a dominant impact on the risk of mould growth at the interior wall surface.

Keywords
Brick masonry, rain water infiltration, heat, air and moisture, moisture sources, cavity walls, ASHRAE 160

Introduction
Since the Second World War, masonry walls are often constructed with cavities for the following two reasons: to avoid water infiltration and to increase the thermal performance compared to solid masonries. The increased watertightness is achieved due to the cavity that interrupts capillary moisture transport and allows water drainage. The thermal advantage of cavities is twofold: the outer cavity leaf has a damping effect from the exterior climate to the inner wall, and the inner wall is protected against moisture which in turn increases the thermal performance. In the literature, the added value of cavity ventilation has been disputed for a long time. Many researchers see cavity ventilation as an increase in the drying potential of the construction, and hence Vos and Tammes (1976) denied the impact of this effect as a conservative approach. Langmans et al. (2016), on the contrary, found that without cavity ventilation the relative humidity in the cavity can increase drastically, which can lead to a saturated construction for a long time span. A detailed study by Van Belleghem on cavity walls with a brick veneer outside leaf and a wood fibre board inner leaf (Van Belleghem et al., 2015) concluded that cavity ventilation is important for the drying rate of the inner wall, whereas the exterior boundary conditions dominate the drying rate of the exterior leaf. In Belgium, cavities of the existing buildings are being filled with insulation due to the increased energy codes. The moisture management and thereby the risk of damage on the construction are drastically altered. Mainly, the drying potential and drainage capacity are reduced due to the cavity filling.

Despite that Salonvaara and Karagiozis (1998) have demonstrated the potential of hygrothermal models to predict the impact of wind-driven rain on masonry constructions, most models are not capable of simulating water infiltration in the wall configurations (Janssen et al., 2007). Typically, 1% of the wind-driven rain is assumed as a reference value for the infiltration rate into cavity wall construction (ASHRAE 160, 2016). About the actual location of the infiltration, on the
contrary, there is no consensus. ASHRAE 160 suggests an implementation of 1% as a uniform load in the construction, while in reality infiltration is proven to occur more locally. Therefore, the implementation of an accurately defined local moisture source might have potential in reproducing reality as shown in a previous study by Carbonez et al. (2015).

To conclude, a correct quantification of the rainwater ingress into brick cavity walls combined with a clear implementation method in heat, air and moisture (HAM) simulations is needed to evaluate the impact on the hygrothermal response of cavity constructions.

**Literature review**

For an elaborate literature review on rainwater infiltration in cavity walls, the authors refer to a previous publication ‘Watertightness of Masonry Walls : An Overview’ by Van Den Bossche et al. (2011). The main findings are summarized below.

Table 1 shows the experiments that were completed by several researchers (ASTM C1715-10, 2010; Brown, 1982; Chiovitti et al., 1999; Ghosh and Melander, 1991; Lacasse et al., 2003; Rathbone, 1982).

<table>
<thead>
<tr>
<th>Reference</th>
<th>Pressure difference (Pa)</th>
<th>Spray rate (L/m²/h)</th>
<th>Number of walls (–)</th>
<th>Type of walls (–)</th>
<th>Minimum and maximum infiltration (%)</th>
<th>Median infiltration (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASTM C1715-10 (2010)</td>
<td>0</td>
<td>138</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>1.2</td>
</tr>
<tr>
<td>ASTM C1715-10 (2010)</td>
<td>500</td>
<td>138</td>
<td>X</td>
<td>X</td>
<td>MMBW</td>
<td>3.4–8.0</td>
</tr>
<tr>
<td>Chiovitti et al. (1999)</td>
<td>500</td>
<td>138</td>
<td>6</td>
<td>MMBW</td>
<td>3.4–8.0</td>
<td>X</td>
</tr>
<tr>
<td>Brown (1982)</td>
<td>479</td>
<td>140</td>
<td>6</td>
<td>MMBW</td>
<td>0.04–0.18</td>
<td>0.06</td>
</tr>
<tr>
<td>Brown (1982)</td>
<td>479</td>
<td>140</td>
<td>6</td>
<td>MCBW</td>
<td>20.4–52.3</td>
<td>31.7</td>
</tr>
<tr>
<td>Ghosh and Melander (1991)</td>
<td>500</td>
<td>138</td>
<td>8</td>
<td>MMBW</td>
<td>&lt;0.005</td>
<td>&lt;0.005</td>
</tr>
<tr>
<td>Rathbone (1982)</td>
<td>500</td>
<td>150</td>
<td>22</td>
<td>MMBW</td>
<td>0–19.6</td>
<td>1.16</td>
</tr>
<tr>
<td>Hens et al. (2004)</td>
<td>25</td>
<td>40</td>
<td>9</td>
<td>MMBW</td>
<td>0.0065–6.0</td>
<td>0.223</td>
</tr>
<tr>
<td>Lacasse et al. (2003)</td>
<td>0 – 400</td>
<td>51–204</td>
<td>4</td>
<td>MMBW</td>
<td>0.47–1.23</td>
<td>0.83</td>
</tr>
<tr>
<td>Hens et al. (2004)</td>
<td>8.5</td>
<td>3.8–6.4</td>
<td>8</td>
<td>GMBW</td>
<td>0.007–64</td>
<td>47.04</td>
</tr>
</tbody>
</table>

X: not specified; X*: not specified, but MMBW can reasonably be assumed; MMBW: mortared masonry brick wall; MCBW: mortared concrete brick wall; GMBW: glued masonry brick wall.
The infiltration rates vary drastically between the different tests, for example, for mortared masonry brick walls the reported infiltration rates range between 0% and 19.6%. The median values are situated between 0% and 3.3%.

The infiltration rates for glued masonry brick walls found by Hens et al. (2004) were observed to be drastically higher, that is, around 47%, which is caused by the open head joints.

The water spray rates and air pressure differences applied during these tests are very extreme and do not represent realistic exterior climate conditions. Also, the duration of the test plays a role, as after a long testing period the façade will be fully saturated which leads to runoff water and increased infiltration.

The moisture content of outer wythe mainly depends on the material properties and the alternation of rain showers and drying periods.

ASHRAE standard 160-2016 proposes a 1% infiltration rate into the wall assembly. Based on the literature review, this is a reasonable approach when no detailed information is available.

Despite the fact that 1% infiltration seems a reasonable assumption based on the available literature, one can question whether these results are representative for brick cavity constructions in general. The reason for this is threefold: the available literature reports mostly only a limited amount of test results, for a specific pressure difference and spray rate, which impedes generalization of the results. Another aspect is that most of the literature reports about tests on fairly perfect new constructions while in reality cracks are present and the overall quality and material properties of the mortar joints and bricks can differ significantly between cases. The conditions of the cavity will also influence the water infiltration to the inner cavity leaf: here the quality of the cavity (clean, no excess mortar), the correct use of wall ties and the width of the cavity are dominant impact parameters. The third and probably most important aspect is that ASHRAE standard 160-2016 does not specify where the infiltration should be located, in the case of a cavity, at the back of the outer leaf (water will be drained in the cavity) or at the outside of the inner leaf (water that was able to cross the cavity). These three aspects that prevent generalization of the results are further investigated in section ‘Experiments’.

**Experiments**

Four outer cavity leaf wall elements are subjected to a series of test procedures, permitting a comparison of the existing standards and an analysis of the amount of water penetration through cavity walls. Existing test procedures and measured leakage rates are discussed and these aspects are related to the test variables and the characteristics of the masonry.
Experimental set-up

Figure 1(a) shows a section through a test sample. The test samples for these experiments were built into a plywood frame; the joints between the frame and the exterior surface of the masonry were sealed with polymer flashings. The net area of the test samples was 0.71 m$^2$ (0.864 m $\times$ 0.818 m). Each sample consisted of a 90-mm brick and cement mortar exterior masonry leaf, an air cavity of approximately 30 mm and a transparent acrylate interior leaf (polymethyl methacrylate) (PMMA) to allow for visual observation of water infiltration. The PMMA sheet was perforated at 10 points in order to simulate a leakage area representative of an inner masonry leaf (2 m$^3$/h/m$^2$ at 50 Pa). Water spray nozzles were mounted at the top of the test element to perform watertightness tests. At the bottom of the test element, two small gutters were created with a polymer membrane through which infiltrated water could be collected and drained to a water collection trough. Thus, water infiltration rates could be measured at the outer and inner sides of the cavity. The two troughs were each standing on a weighing scale with a precision of $\pm 0.1$ g. The amount of water being drained was measured and logged every 30 s. Note that a tubing system ensures that the pressure in the trough is equal to the pressure in the cavity to exclude any additional driving forces to the system.

The four-brick masonry veneer elements were built with differences in workmanship and curing (Table 2). In order to reflect the degraded and weathered state of old masonry, the workmanship of the masonry was chosen to be poor for two of the four wall elements. In these two test walls, the bricks were laid while a time span of 1 min was kept between the application of the mortar layer and the next brick layer (five times slower than normal practice). This practice affects the degree of bond between mortar and bricks and increases the risk of microcracks. In the two other walls, the bricks were laid according to normal practice as a reference. Furthermore, in one of each of the walls with poor workmanship and with normal practice, cardboard of 1 mm (red) and 2 mm (blue) thick was installed into the joints to simulate larger cracks (Figure 1(b)). The size of these cracks was selected

![Figure 1](image-url)

**Figure 1.** Test sample, (a) section and (b) front view, on which the locations of the artificial cracks is indicated.
based on field experience: smaller cracks are often neglected during inspection, whereas larger cracks are typically repaired. The selected crack sizes are of interest due to ongoing debate concerning infiltration risks. Finally, in all elements wall ties were included. Apart from the three common horizontal wall ties, three wall ties inclined inwards were also installed; these intend to simulate poor workmanship. Joints were not separately pointed. Figure 1(b) shows a test element with the locations of the larger purpose built cracks and the location of the horizontal (H) and inclined (I) wall ties. Prior to each test, the brick masonry veneer elements were wetted with a water spray rate of 2 L/min m² during 20 min, to attain full saturation.

**Test protocol**

In a first step, the wall elements were subjected to a series of test procedures in order to relate cavity infiltration rates to the applied water spray rate and thereby permit evaluating the reliability of the existing test procedures. Both static and cyclic test methods were applied to assess the degree of watertightness of the test samples. Since the test conditions described in the standards correspond to low occurrence probabilities of a real climate, a Pareto test procedure (Van Den Bossche et al., 2013a, 2013b) was also used considering the realistic co-occurrence of rain and wind events. The test samples were chosen to mimic buildings having a height of 15 m, located in a coastal area, and subjected to extreme weather events.

The static test standards used for this research were NEN 2778 (2004) and ASTM E514-02 (2009). The NEN 2778 is a Dutch standard to determine the watertightness level of constructions, based on two different test phases: (1) a constant water spray rate of 2 L/min m² (considered representative value as compared to 8.33 L/min used in standard and an extreme value for water spray rate) and an increasing pressure difference are applied to the test sample; maximum air pressure to be applied is 300 Pa; (2) no air pressure has to be applied and water is sprayed in a 10-min interval; 1-min spraying at a water spray rate of 2 L/min m² and 9 min without spraying in total over a time span of 4 h. In this study, only part 1 of the NEN 2778 was analysed.

The ASTM E514-09 is a standard test method for determining the resistance to water penetration and leakage through masonry subjected to wind-driven rain. During the test, a water spray rate of 2.3 L/min m² is imposed, as well as a constant air pressure difference of 500 Pa. The water supply and pressure difference are to be maintained for at least 4 h.
The European standard NBN EN 12865 (2001) is used to determine the resistance of external wall systems to driving rain under pulsating air pressure. The standard describes two procedures: one for qualitative testing (steps of 10 min after 20 min of initial wetting) and one for quantitative testing (steps of 60 min). In contrast to the static test standards, the pressure difference is not a constant value. Pressure pulses are applied in cycles of 15 s, from 0 Pa to the maximum pressure level (varying from 150 to 600 Pa). A constant water spray rate of $2 \text{ L/min m}^2$ is applied to the test sample.

During a rain event, high wind speeds are mostly accompanied by low rainfall intensity, whereas heavy rainfall co-occurs with low wind speeds. To simulate realistic climatic conditions during watertightness tests, a Pareto front analysis was used to determine test parameters. Based on 10 years of 10-min data collected in Uccle (Belgium), Van Den Bossche developed a Pareto test sequence (Van Den Bossche et al., 2013a, 2013b). This test sequence yields a more reliable performance assessment because it addresses different types of failure mechanisms and both static and cyclic conditions. The derived test parameters are only valid for the specific location of the weather station where data were collected and the specific period over which the data were averaged. Hence, test parameters were adapted to represent rain events on a 15-m high building, located in a coastal area. The Pareto test protocol is undertaken over three time periods: a 10-min interval, a 1-min interval and 3-s pressure pulses. In a first test sequence, high water spray rates and low wind pressures are applied for all time periods, followed by a sequence with moderate conditions and finally a sequence is implemented with low water spray rates and high wind pressures.

**Results**

To evaluate the existing test procedures and measured leakage rates, a series of watertightness tests were executed and test results were analysed. As previously mentioned, four test samples were subjected to four test standards (NEN 2778, ASTM E517, EN 12865 and a Pareto procedure).

**Amount of water infiltration.** The total amount of water infiltration during the full duration of the test is compared to the total amount of water applied to the test elements. Table 3 shows the percentage of infiltrated water for the different test samples and test methods over the entire time span of the test. The results show that good workmanship, represented by K1, results in the lowest amount of water infiltration. It is clear that test sample K4, the sample with cracks and poor workmanship, shows the highest amount of water infiltration for all test procedures. It should be noted that although test samples K2 (cracks) and K3 (poor workmanship) are not well executed, the amount of water infiltration has the same order of magnitude as reported for K1. This indicates two things: first, that the combined effect of cracks and poor workmanship has a far bigger impact than each of them separately, and second, that the variability on the wall assemblies is not negligible,
but unfortunately inherent to this type of construction. As expected, the choice of the test method has a significant impact on both absolute and relative infiltration.

Furthermore, the measured water infiltration rates in this study are high compared to the test results reported in the literature discussed earlier. The information provided in Table 1 shows that the infiltration in walls with an exterior brick veneer covers a wide range of values for water infiltration at 500 Pa pressure difference between approximately 0% and 20%, with median values between 0% and 5%. ASTM standard C1715-10 (2010) offers details on historical watertightness data of masonry walls: a median penetration percentage of 3% is reported at 500 Pa and 1% without pressure difference. The discrepancy between the high infiltration rates measured in this study (Table 3 and Figure 3) and the rates reported in the literature (Table 1) shows that the moisture loads in walls with degraded façades (as the ones mimicked here) may be substantially higher than what is typically expected in new brick veneer walls. A study performed by Hens et al. (2004) on glued brick walls confirms this observation. In these types of walls, the brick layers are glued on top of each other with open head joints and no pointing. The tests on the glued veneer walls showed water infiltration quantities in the range of our results: a median value of 47% was reported.

Part of the water infiltration quantities were observed to reach the opposite side of the cavity and drain along the PMMA sheet. In practice, these quantities would be absorbed and/or transferred in the inner masonry leaf and possibly lead to rainwater penetration at the interior wall surface. Two routes for water ingress to the opposite side of the cavity were observed (Figure 2). The main route resulted from water running off at the cavity side of the exterior masonry leaf, dripping on extruded mortar joints and splashing to the opposite side of the cavity. Another route resulted from wrongly sloping wall ties leading to runoff water across the cavity. These phenomena were observed in all four test samples. They also occurred during the water infiltration tests with no pressure difference, a few minutes after the first water leakage to the cavity was visible. During the tests with 500 Pa pressure difference, the phenomena were more pronounced and droplets running from extruded mortar joints were blown to the opposite side of the cavity. This resulted in a large fraction of the infiltration quantity reaching the opposite side. These results are further discussed in section ‘Modelling of water infiltrations to the inner wall’.

### Table 3. Percentage of water infiltration across the brick veneer cladding.

<table>
<thead>
<tr>
<th>Test sample</th>
<th>NEN 2778 (%)</th>
<th>ASTM E514 (%)</th>
<th>EN 12865 (%)</th>
<th>Pareto (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>K1</td>
<td>22</td>
<td>25</td>
<td>15</td>
<td>28</td>
</tr>
<tr>
<td>K2</td>
<td>22</td>
<td>33</td>
<td>14</td>
<td>24</td>
</tr>
<tr>
<td>K3</td>
<td>23</td>
<td>40</td>
<td>19</td>
<td>34</td>
</tr>
<tr>
<td>K4</td>
<td>52</td>
<td>48</td>
<td>34</td>
<td>55</td>
</tr>
</tbody>
</table>
Evaluation of test standards. To evaluate the watertightness of brick cavity walls, a realistic and reliable evaluation method is required. As a first step, static and cyclic test methods are compared. Second, the impact of water spray rate and pressure difference are investigated.

At the 300 Pa pressure difference test phase, of both the cyclic and static test methods, the infiltration rate for each test element is listed in Table 4. It is clear that cyclic tests show less water infiltration, as compared to infiltrations under static loads. This is partially due to the fact that during the cyclic test, with pulses from 0 to 300 Pa, the average pressure difference is lower. Another potential reason is that during the cyclic pressures test continuous water infiltration is interrupted; more information on this can be found in the study by Van Den Bossche (2013). These results are in accordance to the results of Lacasse et al. (2003). On average, the water infiltration rate in cyclic tests is 36% lower, this emphasizes the sensitivity of the results to the selected test method.

Figure 3 shows the infiltration rate as a function of pressure difference for all test samples and for different test procedures. First, the test samples were analysed to investigate the influence of workmanship on the watertightness performance. The results for K1, K2 and K3 are fairly similar (Table 4), whereas the poor workmanship of sample K4 already entails high infiltration rates at low pressure differences. In general, the water infiltration rate will increase for an increasing pressure difference. For all test samples, water infiltration starts at a pressure difference of...
0 Pa, which indicates that the water spray rate and the occurrence of runoff are the predominant parameters for water infiltration of brick masonry veneer walls. Since the masonry wall is saturated at the beginning of every test, water starts running down the masonry immediately, entailing a hydrostatic pressure on the wall, which induces the movement of water through the cracks towards the cavity. Although the existing standards currently assume that air pressure difference is the most important parameter for water infiltration, these results indicate that for brick masonry veneer walls, this is not necessarily the case. It can also be seen that, although the ASTM E514 test standard applies a high pressure difference, the infiltration rates are lower as compared to a pressure difference of, for example, 300 Pa for the NEN 2778 standard. The results of the static test procedures, NEN 2778 and ASTM E514, indicate that the influence of the pressure difference is often overestimated.

The high percentage of water infiltration obtained from testing to the ASTM E514 standard as compared to the NEN 2778 standard, reported in Table 3, seems to disagree with the results in Figure 3, as these values represent an average infiltration over the full duration of the test procedure. For the ASTM E514 standard,
there was constantly a high 500 Pa pressure difference, whereas for the NEN 2778 standard the pressure difference varied between 0 and 300 Pa.

**Discussion and conclusions**

In this study, a series of watertightness tests were performed on non-insulated cavity walls to assess the watertightness performance of cavity walls for a cavity width of 30 mm. This was done in a series of laboratory tests in which four test samples were subjected to a water spray rate and pressure difference defined by four test standards.

The workmanship of the masonry in the test elements was chosen to be poor to reflect the degraded and weathered state of historic masonry in which cavity insulation may subsequently be applied as a retrofit measure. The measured water infiltration rates in the test walls were an order of magnitude higher than the rates reported in the literature for brick masonry veneer walls. This shows that the moisture loads in walls with degraded façades may be substantially higher than what is expected in newly built brick veneer walls. Hence, a good quality of existing masonry may be a first condition to allow for retrofit cavity wall insulation without increasing the risk to water penetration.

Furthermore, it was concluded that the air pressure difference is not always the dominating parameter in watertightness tests. The influence of the water spray rate and runoff due to saturation of the masonry wall should be taken into account when developing a reliable and realistic test protocol.

Finally, it should be noted that the test conditions imposed in this research relate to extreme rain events which have a low probability of occurring (Van Den Bossche et al., 2013a, 2013b).

**Simulations**

As realistic climate conditions are difficult to mimic in the laboratory, the experimental results are translated into infiltration rates dependent on the applied pressure difference. These infiltration rates are then implemented with various methods in an HAM simulation model to evaluate the impact of the infiltrations under more realistic wind-driven rain loads for several damage criteria. As a cavity is able to drain infiltrated rainwater vertically, adding an infiltration source in the cavity would not make sense; only the amount of water that reaches the inner side of the cavity, more specifically, the water that was drained along the PMMA in the above-described experiments, should be numerically implemented at the outside surface of the inner wall in the modelled assembly. The implementation of these infiltrations is further discussed in section ‘Modelling of water infiltrations to the inner wall’.
Model

The hygrothermal behaviour of different cavity walls was investigated using version 5.9 of the HAM simulation programme Delphin (Grunewald, 1996). Weather data for Essen (Germany) were used for the external climatic conditions. The internal climatic conditions are related to the outdoor temperature. The indoor temperature linearly fluctuates between set point temperatures of 20°C and 25°C if the ambient temperature varies between 10°C and 20°C. For a higher/lower ambient temperature, the indoor temperature is fixed at 25°C/20°C, respectively. The indoor relative humidity is allowed to fluctuate linearly between 35% and 65% for, respectively, an ambient temperature between 10°C and 20°C (EN ISO 13788, 2001). The inner boundary heat transfer coefficient is fixed at 0.2 m²K/W as in contrast to heat loss calculations (0.13 m²K/W); a reduced heat transfer coefficient is needed for the assessment of interstitial condensation risks (EN ISO 13788, 2001; Janssens et al., 2007). The hygrothermal simulations are run for a period of 3 years, using hourly time steps. To avoid the assumed initial conditions affecting the output, only the data of the third year were evaluated and reported. Material properties from the Delphin material database were used as reported in Table 5 (Grunewald et al., 2003).

The simulated façade consisted of an outer cavity leaf of 90 mm, a 30-mm air cavity, a 140-mm inner wall and a 10-mm gypsum plaster. This is the predominant wall configuration for residential buildings in Belgium built in the second half of the 20th century (Figure 4). The masonries were simplified to homogeneous brick layers. The porosity of the air layer was chosen at a value of 0.0067 m³/m³. This corresponds to a moisture content of 0.200 kg/m² in a cavity of 30 mm. At this moisture content, runoff is considered to occur which will cause water to drain from the construction (Meert, 2000). In Delphin, excess water is automatically

### Table 5. Hygrothermal material properties.

<table>
<thead>
<tr>
<th>Material</th>
<th>(t) (mm)</th>
<th>(\lambda) (W/mK)</th>
<th>(\mu) (–)</th>
<th>(\rho) (kg/m³)</th>
<th>(\theta_{\text{por}}) (m²/m³)</th>
<th>(\theta_{\text{cap}}) (m²/m³)</th>
<th>(A_w) (kg/m² s⁰.⁵)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer cavity leaf</td>
<td>Classic brick (Cla)</td>
<td>90</td>
<td>0.80</td>
<td>8.3</td>
<td>1710.0</td>
<td>0.330</td>
<td>0.266</td>
</tr>
<tr>
<td></td>
<td>High-uptake brick (Hi)</td>
<td>90</td>
<td>0.43</td>
<td>7.2</td>
<td>1469.3</td>
<td>0.446</td>
<td>0.420</td>
</tr>
<tr>
<td></td>
<td>Low-uptake brick (Lo)</td>
<td>90</td>
<td>0.93</td>
<td>26.5</td>
<td>1966.5</td>
<td>0.258</td>
<td>0.130</td>
</tr>
<tr>
<td>Cavity</td>
<td>Air cavity 30 mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Interior wall</td>
<td>Normal brick</td>
<td>140</td>
<td>0.55</td>
<td>19.0</td>
<td>1400</td>
<td>0.354</td>
<td>0.265</td>
</tr>
<tr>
<td>Interior plaster</td>
<td>Gypsum plaster</td>
<td>10</td>
<td>0.26</td>
<td>11.3</td>
<td>1043</td>
<td>0.606</td>
<td>0.350</td>
</tr>
</tbody>
</table>

\(t\): thickness, \(\lambda\): the thermal conductivity, \(\mu\): the vapour diffusion resistance, \(\rho\): density, \(\theta_{\text{por}}\): the open porosity, \(\theta_{\text{cap}}\): the capillary moisture content; \(A_w\): the capillary absorption coefficient.
deleted from the equation when moisture contents higher than the porosity are reached.

The cavity ventilation is accounted for by applying a constant air change rate (ACR) of 5. This means the model assumes that the air in the cavity is replaced five times in 1 h by air with the same temperature and relative humidity as the outdoor climate; no fluid dynamics are considered in this process. Furthermore, long wave radiation exchange between the two sides of the cavity is also taken into account.

**Modelling of water infiltrations to the inner wall**

During the watertightness experiments described earlier, some of the water that infiltrated the cavity reached the opposite side of the cavity mainly by dripping on extruded mortar joints and then splashing onto the PMMA sheet at the interior side of the cavity. In practice, this infiltration water would then be absorbed by the inner masonry leaf. In the current HAM models, water ingress can be taken into account by adding a moisture source to the construction. However, very little is known on where this moisture source should be located and at which rate water should be added to the construction. Currently, in the rare cases that infiltration is accounted for, it is included according to the ASHRAE standard 160-2016. This standard suggests to add 1% of the total wind driven rain (WDR) at the exterior surface of the water resistant barrier, yet this implicates a uniform distribution for water infiltration. As the previous experiments have shown that infiltration onto the inner cavity leaf occurred at specific locations (extruded mortar joints, wrongly sloping wall ties), a point source is considered more appropriate for this type of wall assembly. Consequently, the infiltration was modelled in Delphin as a point source comprising an area of 10 mm $\times$ 5 mm and located in the inner cavity leaf adjacent to the cavity (Figure 4: MS 2). The source is rectangular as now the simulation is symmetric over the $x$-axis, which reduces the computational time compared to simulating a centralized source. The height of the assembly was chosen as 150 mm, as this was found optimal to visualize the redistribution of the moisture originating from the point source for a limited computational cost. The optimal size of the source (MS 2) was determined to avoid reaching the saturation moisture content and thus having Delphin delete the infiltrating moisture.

The quantity of the water infiltration that reaches the inner cavity leaf and is implemented by the moisture source is based on the measurements from the watertightness experiments in section ‘Experiments’ instead of the 1% infiltration of the ASHRAE standard 160-2016. The rate of water ingress in the cavity is determined by linearly interpolating the measured results from the static tests (NEN 2778; Figure 3: K4). The cyclic data were not used as converting the cyclic experimental data to a moisture source would entail higher uncertainties: a hygrothermal simulation is executed based on averaged hourly data and the variation within the hourly data is unknown. In perspective of generalization, the static test standard is also the best choice as in the literature more data are available.
Based on several tests, the ratio, $r$, between the infiltrating water that drains from the cavity at the back of the outer cavity leaf and the amount of water that was able to cross the cavity (reached the PMMA plate) is given by the following relation

$$r = 9.1 \times 10^{-5} \times \Delta p + 1.72 \times 10^{-3}$$

(1)

where $r$ is the ratio of infiltration to the interior cavity leaf over the total infiltration rate. When all infiltrated water would reach the inner wall, the value of $r$ would be 1, whereas if no water reaches the interior leaf, the value of $r$ would be 0. In accordance to our expectations, values for $r$ range between 0.1% and 3% depending on the pressure difference ($\Delta p$).

This ratio is applied to the test results for wall K4 since this wall had the highest measured infiltration rates (Figure 3), and thereby was found representative for highly weathered historical cavity constructions. If this infiltration rate is then expressed as a percentage of the water supply, the following infiltration functions are obtained expressing the infiltration percentage at the inner cavity side ($\text{INF}_{\text{int}}$ (−)) and outer cavity side ($\text{INF}_{\text{out}}$ (−)) in relation to the overall pressure difference ($\Delta p$ (Pa)) over the wall (Figure 5)

$$\text{INF}_{\text{int}} = 7.89 \times 10^{-5} \times \Delta p + 3.60 \times 10^{-4}$$

(2)
In addition, the mean wind pressure can be related to the characteristic 10-min mean wind velocity based on Eurocode 1 (EN 1991-1-4:2005 + A1, 2010) and Bernoulli’s law

\[
p_m = 0.625 \times (c_{pe} - c_{pi}) \times \left[ 0.19 \times \left( \frac{z_0}{0.05} \right)^{0.07} \times \ln \left( \frac{z}{z_0} \right) \right]^2 \times v_{b,0}^2
\]

where \( p_m \) is the mean velocity pressure for 10-min averaging periods (Pa), \( c_{pe} \) is the external pressure coefficient (maximum value of 1 according to Eurocode 1), \( c_{pi} \) is the internal pressure coefficient (value of 0.3 (Eurocode 1)), \( z_0 \) is the roughness length (m; value of 0.05 for terrain category II), \( z \) is the height of the wind speed measurement (m; 10 m) and \( v_{b,0} \) is the fundamental value of the basic wind velocity (m/s).

To determine the infiltration for every time step, the infiltration percentage is applied to the value of WDR intensity. The WDR intensity is determined using the following relation (Blocken and Carmeliet, 2004)

\[
R_{WDR} = \alpha \times U \times R_h \times \cos \theta
\]

where \( R_{WDR} \) is the WDR intensity (mm/h), \( \alpha \) is the adapted driving rain coefficient (s/m, for which data tables are used determined via simulations on the VLIET building; Blocken and Carmeliet, 2004), \( U \) is the wind speed (m/s), \( R_h \) is the
horizontal rainfall intensity (mm/h) and $\theta$ is the angle between the wind direction and the line normal to the wall ($^\circ$).

The infiltration rate is quantified hourly in accordance with the time step of the available climate data. Based on preliminary simulations, several orientations are compared based on WDR, mould growth and critical freeze–thaw cycles. The South-West orientation is found critical for the chosen exterior climate and thus applied for each of the following simulations.

**Simulation methodologies**

The impact of rainwater infiltration on the hygrothermal behaviour of the cavity wall was investigated for the three brick types by different modelling approaches. Table 6 shows an overview of the different variations which have been simulated; overall, eight different modelling approaches were evaluated. As a reference the three constructions (Table 5) were simulated with commonly used methods: no infiltration (Method 1), a uniform infiltration of 1% of the WDR as proposed in ASHRAE 160 (Method 2) (2016) and additionally the use of a point source instead of a uniform infiltration (Method 3). For Method 4, the infiltration rate, implemented as a point source, was calculated for each time step based on equation (2) and translated as an actual infiltration by multiplication with the WDR (equation (5)). For Methods 4–7, the calculated water infiltration was only implemented when $R_{WDR} > 0$, and the wind direction was within a range of 45° from the normal to the building façade, only then are wind effects assumed to pressurize the building façade. In Method 5, an additional condition for water infiltration was added.

<table>
<thead>
<tr>
<th>Method</th>
<th>Setup ($X = Cla, Hi$ or $Lo$)</th>
<th>Infiltration</th>
<th>Source type and location</th>
<th>Number of iterations</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$X$-Air-Nor-Gyp</td>
<td>No infiltration</td>
<td>Uniform (MS 1)</td>
<td>–</td>
</tr>
<tr>
<td>2</td>
<td>$X$-Air-Nor-Gyp</td>
<td>1% of $R_{WDR}$</td>
<td>Uniform (MS 1)</td>
<td>–</td>
</tr>
<tr>
<td>3</td>
<td>$X$-Air-Nor-Gyp</td>
<td>1% of $R_{WDR}$</td>
<td>Point (MS 2)</td>
<td>–</td>
</tr>
<tr>
<td>4</td>
<td>$X$-Air-Nor-Gyp</td>
<td>Equation (2) sat. independent</td>
<td>Point (MS 2)</td>
<td>–</td>
</tr>
<tr>
<td>5</td>
<td>$X$-Air-Nor-Gyp</td>
<td>Equation (2) sat. dependent</td>
<td>Point (MS 2)</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td>$X$-Air-Nor-Gyp</td>
<td>First: equation (3) sat. dependent, Second: equation (3) sat. dependent</td>
<td>Uniform (MS 3)</td>
<td>2</td>
</tr>
<tr>
<td>7</td>
<td>$X$-Air-Nor-Gyp</td>
<td>Changed ACR</td>
<td>Point/uniform (MS 2 and 3)</td>
<td>1</td>
</tr>
<tr>
<td>8</td>
<td>$X$-Air-Nor-Gyp</td>
<td>Capillary bridge</td>
<td>Uniform (MS 3)</td>
<td>–</td>
</tr>
</tbody>
</table>

ACR: air change rate; Cla: classic brick; Hi: high-uptake brick; Lo: low-uptake brick; Air: air cavity; Nor: normal brick; Gyp: gypsum plaster; sat.: saturation.
to Method 4; in this instance, infiltration was only simulated if the façade surface was capillary saturated at a depth of 5 mm or if the WDR intensity exceeded the brick masonry absorption rate. As long as the façade is not capillary saturated or as long as the water supply rate is less than the rate of absorption of the masonry, the masonry is able to absorb the rainwater that is deposited on the façade and no runoff, nor infiltration will occur. As for this method, the saturation at a depth of 5 mm is needed to quantify the infiltration rate, a one-dimensional (1D) simulation without infiltration was first executed to define the degree of saturation at a 5-mm depth over a full year for the simulated construction subjected to the same climate conditions. Currently, a real-time coupling between the degree of saturation, the construction and the moisture source is not possible in the software, therefore, this iterative method was used. The depth of 5 mm to evaluate the surface saturation was chosen to avoid numerical instability due to boundary effects. The value of 5 mm depth is also often used to evaluate the risk of frost damage (Vereecken et al., 2015).

Method 6 increases the complexity of the simulation process by adding an additional iteration to calculate the infiltration rate at the inner cavity leaf; the intent is to increase the comparable realism of the simulation to actual conditions in the field. First, the saturation of the surface was determined with a 1D simulation without moisture sources. Then, in a second 1D simulation a uniform moisture source equal to the infiltration INF_{ext} (equations (3), MS 3) was implemented at the inside of the outer cavity leaf (quantified with the degree of saturation the first simulation). Based on this second simulation, the saturation at a depth of 5 mm was re-evaluated and a point moisture source for the final simulation was defined. Thus, in the final simulation the infiltration at the back of the outer leaf (INF_{out}) was retained using the moisture source defined by equation (3), MS 3.

To evaluate the impact of the ACR, Method 7 was devised, and it was the same as Method 6 with the exception that the ACR of 5 in the cavity was replaced by 0 and 10 as research by Langmans has showed that cavity ventilation behind brick veneer corresponds to an ACR between 1 and 10 (Langmans et al., 2016). In Method 8, no infiltration at the inner wall was assumed but a connection between the outer and inner cavity leaf by a 5-mm high capillary bridge with the same material properties as the outer cavity leaf was made representing the potential impact of a capillary bridge due to mortar or construction rubble present in the cavity. The bridge was assumed to have the same material properties as the outer cavity leaf. The moisture source representing the infiltration at the back of the outer leaf (INF_{out}) was kept in place as in Methods 6 and 7.

**Criteria**

The performance of the cavity wall was evaluated by means of two sets of criteria: criteria for mould growth and criteria for frost damage. First, the risk for mould growth was evaluated by assessing whether the conditions of the wall would give rise to mould growth at the inner surface of the wall. Since mould growth should be avoided, this is considered an absolute criterion. The risk of mould growth was
determined using the updated VTT-model (Ojanen et al., 2011; Viitanen et al., 2010). The sensitivity class ‘medium resistant’ and decline class ‘almost no decline’ were assumed. In this empirical prediction model, the growth development is expressed by the mould index M based on data for the temperature and relative humidity. This index gives an indication of the risk of mould growth. The different mould index classes that are used in the model are listed in Table 7. The mould index was assessed at the inner surface of the cavity wall at the height of the moisture source.

Second, the risk for frost damage was evaluated by means of the number of critical freeze–thaw cycles and the ice mass density at a depth of 5 mm, measured from the exterior surface of the simulated wall, at the same height as the moisture source. Typically, a critical freeze–thaw cycle at this depth induces frost damage (Vereecken et al., 2015). A freeze–thaw cycle is considered critical if the saturation of the masonry exceeds critical saturation. A total of 90% of water in the pore volume is often considered to be critical since the volume of water increases by $6 \times 10\%$ during freezing. However, in some materials, the stresses at saturation levels lower than even 25% can already give rise to damage (Straube et al., 2010). This indicates that the value for critical saturation of a material is in fact dependent on the pore system and strength properties and can therefore not be generalized. Thus, to gain insight into the importance of the value for the critical saturation level, critical saturation levels of both 90% and 25% were investigated. A low critical saturation level leads to a greater number of critical freeze–thaw cycles, which in turn allows a better evaluation of the impact of different design choices on the risk of frost damage (Calle and Van Den Bossche, 2017). The mean and maximum ice mass density give more detailed insight of the severity of the freezing process.

If water infiltration occurs, it will also affect the heat flow through a cavity wall since the thermal conductivity of a material increases with increasing moisture contents. The cumulative heat flux is therefore investigated at the inner surface at the level of the moisture source. Consequently, although this is not representative of the complete wall, it does give an indication of the impact of the water penetration on the heat flux.

### Table 7. Mould index classes in the VTT-model (Viitanen and Ojanen, 2007).

<table>
<thead>
<tr>
<th>Index</th>
<th>Growth rate</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>No mould growth</td>
<td>Spores not activated</td>
</tr>
<tr>
<td>1</td>
<td>Small amounts of mould on surface</td>
<td>Initial stages of growth</td>
</tr>
<tr>
<td>2</td>
<td>$&lt;10%$ coverage of mould on surface</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>10%–30% coverage of mould on surface</td>
<td>New spores produced</td>
</tr>
<tr>
<td>4</td>
<td>30%–70% coverage of mould on surface</td>
<td>Moderate growth</td>
</tr>
<tr>
<td>5</td>
<td>$&gt;70%$ coverage of mould on surface</td>
<td>Plenty of growth</td>
</tr>
<tr>
<td>6</td>
<td>Very heavy, dense mould growth covers nearly 100%</td>
<td>Coverage around 100%</td>
</tr>
</tbody>
</table>

Note: VTT refers to VTT Technical Research Center of Finland Lt.
Results

The information provided in Table 8 gives an overview of the simulation results for each criterion as well as the yearly water infiltration simulated by the moisture sources at the inner wall for each of the eight simulation methods. If a moisture source was implemented at the back of the cavity surface of the exterior brick wall (Methods 6–8), the yearly infiltration rate is shown between brackets. The values for the yearly amount of infiltration that reaches the inner cavity leaf show differences between the simulation methods. As described in section ‘Simulation methodologies’, the saturation of the exterior masonry plays a decisive role in the more advanced simulation methods, that is, Methods 5–7. If the exterior cavity leaf is in perfect condition (no cracks, good workmanship) or if a ‘perfect’ water-repellent finish is applied on the façade surface (hydrophobic treatment, paint), no water infiltration will reach the inner cavity leaf. The higher the sorptivity of the outer cavity leaf, the lower the infiltration since a brick with higher sorptivity will be able to absorb more of the impinging rain without any runoff occurring (Table 8, Method 5). For all methods, the yearly amount of water infiltration that reaches the inner cavity leaf for realistic climate conditions was found to be relatively low, that is, ±0.5% of the WDR or even lower.

Figure 7 shows the average moisture mass density (MMD) of the inner wall; due to the limited infiltration, the average MMD is low but the differences between the simulation approaches are clearly visible. As water infiltration is a local effect, simulated with a local source, the water that reaches the inner cavity leaf is quickly distributed in the wall. This results in the fact that the mould index remains very low for almost all cases. The added value of a point source in comparison to a uniform source is hence limited, when an interior wall with a high moisture redistribution capacity is present. The risk for mould growth remains below 0.1 for all variations except for one: Method 8 (the capillary bridge).

The added value of the additional iteration examined in Method 6 is limited for evaluation of the risk of mould growth at the interior surface, and due to the complexity it is not found applicable for practice. The risk of frost damage is evidently increased due to the added moisture source at the cavity surface of the exterior brick wall. Changes in the ACR only have a small impact on the drying rate of the inner wall of the construction (Figure 6). Potentially, the ACR will have a bigger impact if the interior wall gets increasingly saturated as indicated by Van Belleghem et al. (2015).

In Figure 6, Method 6 shows a higher average MMD compared to that obtained from use of simulation Methods 2–5 due to a reduced drying rate towards the cavity; this is to be noted considering that the total infiltration towards the inner wall was less than half of that obtained in Method 2 (the traditional 1% uniform infiltration; Table 8). This indicates that the moisture content of the outer cavity leaf can have an impact on the drying potential of the inner leaf. However, the risk to mould growth in the inner wall is unlikely to be affected given that there is not sufficient moisture accumulation in the cavity arising from the presence of moisture in the outer leaf.
Table 8. Calculated yearly infiltration, mould index, number of critical freeze–thaw cycles and heat flux as obtained from the different simulation methods.

<table>
<thead>
<tr>
<th>Case (method: construction, type of infiltration.)</th>
<th>Yearly infiltration (L)</th>
<th>Maximum mould index (–)</th>
<th>Heat flux (kW/m²)</th>
<th>FTCcr at 5 mm (–)</th>
<th>Ice mass density during freezing (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>Scr = 0.25</strong></td>
</tr>
<tr>
<td>M1: -Air-Nor-Gyp, no infil.</td>
<td>0</td>
<td>0.0001141</td>
<td>139.346</td>
<td>9</td>
<td>0</td>
</tr>
<tr>
<td>M1: -Air-Nor-Gyp, no infil.</td>
<td>0</td>
<td>0.0000217</td>
<td>124.637</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>M1: -Air-Nor-Gyp, no infil.</td>
<td>0</td>
<td>0.0011740</td>
<td>142.183</td>
<td>16</td>
<td>0</td>
</tr>
<tr>
<td>M2: -Air-Nor-Gyp, 1% uni.</td>
<td>0.3530</td>
<td>0.0001134</td>
<td>139.740</td>
<td>9</td>
<td>0</td>
</tr>
<tr>
<td>M2: -Air-Nor-Gyp, 1% uni.</td>
<td>0.3530</td>
<td>0.0000159</td>
<td>125.120</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>M2: -Air-Nor-Gyp, 1% uni.</td>
<td>0.3530</td>
<td>0.0001462</td>
<td>142.590</td>
<td>16</td>
<td>0</td>
</tr>
<tr>
<td>M3: -Air-Nor-Gyp, 1% point</td>
<td>0.3530</td>
<td>0.0009433</td>
<td>139.799</td>
<td>9</td>
<td>0</td>
</tr>
<tr>
<td>M3: -Air-Nor-Gyp, 1% point</td>
<td>0.3530</td>
<td>0.0001964</td>
<td>125.257</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>M3: -Air-Nor-Gyp, 1% point</td>
<td>0.3530</td>
<td>0.0012430</td>
<td>142.688</td>
<td>16</td>
<td>0</td>
</tr>
<tr>
<td>M4: -Air-Nor-Gyp, sat.-indep.</td>
<td>0.1545</td>
<td>0.0001152</td>
<td>139.472</td>
<td>9</td>
<td>0</td>
</tr>
<tr>
<td>M4: -Air-Nor-Gyp, sat.-indep.</td>
<td>0.1545</td>
<td>0.0000239</td>
<td>124.892</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>M4: -Air-Nor-Gyp, sat.-indep.</td>
<td>0.1545</td>
<td>0.0001511</td>
<td>142.322</td>
<td>16</td>
<td>0</td>
</tr>
<tr>
<td>M5: -Air-Nor-Gyp, sat.-dep.</td>
<td>0.1337</td>
<td>0.0001154</td>
<td>139.473</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>M5: -Air-Nor-Gyp, sat.-dep.</td>
<td>0.1199</td>
<td>0.0000239</td>
<td>124.832</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>M5: -Air-Nor-Gyp, sat.-dep.</td>
<td>0.1475</td>
<td>0.0001510</td>
<td>142.294</td>
<td>15</td>
<td>0</td>
</tr>
<tr>
<td>M6: -Air-Nor-Gyp, sat.-dep.2</td>
<td>0.1391 (1.1182)</td>
<td>0.0009357</td>
<td>142.267</td>
<td>17</td>
<td>1</td>
</tr>
<tr>
<td>M7: Cla-Air-Nor-Gyp, 0 ACR</td>
<td>0.1391 (1.1182)</td>
<td>0.0009700</td>
<td>142.093</td>
<td>17</td>
<td>1</td>
</tr>
<tr>
<td>M7: Cla-Air-Nor-Gyp, 10 ACR</td>
<td>0.1391 (1.1182)</td>
<td>0.00091480</td>
<td>143.228</td>
<td>17</td>
<td>1</td>
</tr>
<tr>
<td>M8: Cla-Air-Nor-Gyp, bridge</td>
<td>(1.1182)</td>
<td>0.5320</td>
<td>161.979</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

ACR: air change rate; Cla: classic brick; Hi: high-uptake brick; Lo: low-uptake brick; Air: air cavity; Nor: normal brick; Gyp: gypsum plaster; infil.: infiltration; indep.: independent; uni.: uniform; sat.: saturation; dep.: dependent; FTCcr: number of critical freeze-thaw cycles.
The results for the cumulative heat flux show that the wetting of the inner cavity leaf by the moisture source only slightly increases (by 0.09%) the heat flux at the moisture source level. ($M1$: Cla-Air-Nor-Gyp, no infil. vs $M5$: Cla-Air-Nor-Gyp, sat.-dep.). This limited amount of infiltration does not significantly influence the heat flux. Due to the generally limited infiltration to the inner wall also the increase in the ACR has a relatively limited impact on the total heat flux as the drying of the inner wall has little impact. On the contrary, the capillary bridge (Method 8) leads to a 16.26% increase in the heat flux due to a far larger infiltration towards the inner masonry wall, and thereby a local increase in thermal conductivity (Figure 7(a)). In total, 6.54 L of moisture was transported at the capillary bridge towards the inner wall as given from the results derived from Method 8 over a time span of 1 year, whereas for Method 6 the moisture source was only 0.139 L. The total moisture transport through the capillary bridges was necessarily very sensible to its contact surface and changes in material properties of the bridge. However, these results indicate that given a reasonable selection of material properties arising from poor workmanship and leading to capillary contact at extruded mortar joints or contact with construction rubble in the cavity, the order of magnitude of the local infiltration rate to the inner wall can easily increase.

The number of critical freeze–thaw cycles gives an indication of the risk for frost damage in the outer leaf. Since there are no criteria which describe the maximum allowed number of critical freeze–thaw cycles, these can only be evaluated relative to one another. The number of critical freeze–thaw cycles appears to be the highest for a cavity wall with a low absorptive outer cavity leaf. However, since the critical saturation is fixed for all materials at a value of 25%, it is possible that in reality the number of critical freeze–thaw cycles will be lower than for the other materials simply because the value for critical saturation is higher. An outer cavity leaf with high absorptivity leads to fewer critical freeze–thaw cycles due to its ability to quickly absorb and release water, causing lower saturations in the outer cavity leaf. The ice mass density shows a similar trend. The mean value is a good indication of the severity in occurrence of freeze–thaw cycles.

**Conclusion**

Water infiltration into brick cavity walls can have a significant impact on the hygrothermal response of the assembly and its long-term performance. Therefore, to obtain a useful understanding of the hygrothermal behaviour of such a type of wall systems, it is first necessary to provide a correct assessment of the amount of water ingress and knowledge of the infiltration process into brick cavity walls. This is especially important if consideration is being given to the energy retrofit of such walls through measures such as filling the cavity with insulation or the installation of insulation on the interior of the wall assembly. To that end, watertightness experiments were conducted to first get to know non-insulated cavity walls. The workmanship of the masonry in the test elements was chosen to be poor to reflect the degraded and weathered state of an aged masonry wall structure.
The measured water infiltration rates in the test walls were an order of magnitude higher than rates reported in the literature for masonry. This can be attributed to the degraded state of the façades, causing substantially higher moisture loads than what is expected in new brick veneer walls. The measurements also showed that the air pressure difference is not always the dominating parameter in water-tightness tests. For all test samples, water infiltration already initiated without a pressure difference. This indicates that the water spray rate and the occurrence of runoff are the predominant parameters for water infiltration. During the water-tightness experiments, part of the water infiltration quantities were observed to reach the opposite site of the cavity, mainly by dripping on extruded mortar joints and then splashing onto the inner side of the cavity (PMMA plate). In addition, wrongly sloping wall ties provided a path for runoff water across the cavity.

**Figure 6.** The average moisture mass density of the inner wall for an outer cavity leaf in brick type: classic brick (Table 5). Method 8 is not mentioned as the average moisture content is far greater (see Figure 7(a)).

The measured water infiltration rates in the test walls were an order of magnitude higher than rates reported in the literature for masonry. This can be attributed to the degraded state of the façades, causing substantially higher moisture loads than what is expected in new brick veneer walls. The measurements also showed that the air pressure difference is not always the dominating parameter in water-tightness tests. For all test samples, water infiltration already initiated without a pressure difference. This indicates that the water spray rate and the occurrence of runoff are the predominant parameters for water infiltration. During the water-tightness experiments, part of the water infiltration quantities were observed to reach the opposite site of the cavity, mainly by dripping on extruded mortar joints and then splashing onto the inner side of the cavity (PMMA plate). In addition, wrongly sloping wall ties provided a path for runoff water across the cavity.

**Figure 7.** Two-dimensional (2D) colour diagram of the moisture mass density (kg/m$^3$) in the simulated sections for Methods 8 (a) and 6 (b) after a rain shower (8200 h).
higher pressure levels, droplets running from extruded mortar joints were blown to the opposite side of the cavity. In practice, all infiltration water that reaches the opposite side of the cavity would be absorbed by the inner masonry leaf.

In those instances where infiltration is currently accounted for in the HAM simulation, this would be included according to the approach given in ASHRAE standard 160-2016. This standard suggests to add 1% of the total WDR at the exterior surface of the water-resistant barrier. However, the measurements on cavity walls showed much greater infiltration rates into cavity walls: up to 21% of the water deposition rate without pressure difference. The infiltration onto the inner cavity leaf on the contrary was far smaller, ranging from 0.03% to 2.6% for, respectively, a 0–300 Pa pressure difference, and occurred only at specific locations in the wall (extruded mortar joints, wrongly sloping wall ties). Therefore, a different simulation approach was applied in which a point source in the inner cavity leaf was used, adjacent to the cavity, simulating water ingress at infiltration rates related to the wind-driven rain and wind pressure loads acting over the wall that were based on a linear correlation derived from static watertightness measurements. In addition, the water infiltration was only simulated if the façade surface was capillary saturated or if the WDR intensity exceeded the absorption speed of the brick masonry structure. The calculated infiltration based on the measurements and the hygrothermal simulations showed that the amount of water infiltration that actually reached the inner cavity leaf of a brick cavity wall is rather low (i.e. $\pm 0.37 \text{ L/m}^2\text{-yr}$ of infiltration in respect to $35 \text{ L/m}^2\text{-yr}$ of wind-driven rain deposition on the façade), given the supposedly realistic pressure differences to which the wall assembly was subjected. Consequently, no risk for mould growth on the inner surface could be determined and the impact of the infiltrating water on the heat flux was also very limited. In addition, the simulation indicated that once a small capillary bridge, due to for example an extruded mortar joint or construction trash, is present in the cavity a strong increase in the risk for mould growth at the interior surface of the construction is possible.

Due to the lack of specific criteria, the risk of frost damage for the different variations could only be evaluated relative to one another. Here, the addition of a moisture source at the interior side of the outer brick leaf induced an increase in the frost risk. This should be taken into account as in reality the infiltration of water into the cavity is drained along the back of the outer masonry leaf.

The results from the parametric study, in which the impact of different design choices (type of outer cavity leaf, orientation and modelling approach) was investigated, showed that next to the watertightness of the exterior masonry and the orientation of the wall, the moisture storage properties of the exterior masonry also have an impact on the amount of water ingress. For bricks with high moisture transport properties, it will take longer before runoff and capillary saturation of the exterior surface occurs and therefore fewer infiltration will occur.

In conclusion, this article presented a methodology to implement the effect of rainwater infiltration into hygrothermal simulations of brick cavity walls. Well-defined test conditions are a prerequisite to convert experimental data towards
moisture sources for HAM simulations. The assessment was done for a brick cavity wall, but the approach can be extended and implemented for other types of wall configurations. Different modelling approaches were evaluated using Delphin 5.9 to develop a robust and reliable assessment methodology. However, an increased accuracy in simulating wall configurations could be obtained with more extended and coupled models. For example, the implementation of wind-driven rain runoff models, or expanding the functionality of moisture sources by direct coupling of the source quantity to the MMD of specific materials in the currently available HAM models, would allow more accurate simulations of the hygrothermal behaviour of wall assemblies in general, and cavity brick walls specifically.

Acknowledgements
Bauklimatic-Dresden is acknowledged for providing a Delphin 5.9 software licence.

Declaration of conflicting interests
The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding
The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This research was funded by the agency for Innovation by Science and Technology-Belgium (IWT), Project IWT-120784, Renofase and Research Foundation – Flanders (FWO), SBO-1S45416N.

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