Hygrothermal assessment of four insulation systems for interior retrofitting of solid masonry walls through calibrated numerical simulations

Jensen, Nickolaj Feldt; Bjarløv, Søren Peter; Rode, Carsten; Møller, Eva B.

Published in:
Building and Environment

Link to article, DOI:
10.1016/j.buildenv.2020.107031

Publication date:
2020

Document Version
Peer reviewed version

Citation (APA):

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.
Hygrothermal assessment of four insulation systems for interior retrofitting of solid masonry walls through calibrated numerical simulations

Nickolaj Feldt Jensen*, Søren Peter Bjarløv*, Carsten Rode*, Eva B. Møller*,

* Department of Civil Engineering, Technical University of Denmark, Brovej 118, 2800 Kgs. Lyngby, Denmark

*Corresponding author.
E-mail addresses: nicf@byg.dtu.dk (Nickolaj Feldt Jensen).

Highlights:

- Hygrothermal assessment of four internal insulation systems
- Study the effects of varying brick and mortar types.
- Study the effects of increased masonry- and insulation thickness
- A reduction of the indoor moisture load improved the hygrothermal conditions
- Two systems were found robust against future climate conditions

Keywords: internal insulation, solid masonry, calibrated hygrothermal simulations, mould modelling, diffusion-open capillary active, diffusion-tight

Abstract

The present research project investigates the hygrothermal performance of four insulation systems for internal retrofitting solid masonry walls with embedded wooden wall plate and beam end. The study was carried out through numerical simulations calibrated with 2-4 years of measurements and material data from a large field experimental in the cool, temperate climate of Lyngby, Denmark. The experiment comprised two 40-foot insulated reefer containers reconfigured with 24 1x2 m holes,
accommodating the solid masonry walls. The calibrated simulation models were used to investigate several untested design variations which included alternative brick and mortar types, masonry and insulation thickness, indoor moisture load and future climate conditions. The findings indicate that a reduction of the indoor moisture load would improve the hygrothermal performance in the interface between wall and insulation, and in the embedded wooden elements. Increased masonry thickness was seen to make the hygrothermal conditions worse due to increased drying time for the built-in moisture, while in the case of low initial moisture content, increased masonry thickness improved the hygrothermal performance in the interface and embedded wooden elements. Increased insulation thickness also made the hygrothermal conditions worse. Regarding the brick and mortar types, the results showed increased relative humidity in the critical locations in the case of high cement mortar compared to low cement mortar. The brick type was however found not to impact the relative humidity levels considerably. Robustness against future climate conditions was seen only for two of the four insulation systems, when combined with exterior hydrophobisation.

1 Introduction

Retrofitting historic building facades has been a hot topic in recent years, due to the considerable energy conservation potential. Odgaard et al. [1] found that 41% of all Danish multi-story residential buildings (3+ floors) were constructed in the period 1850-1930, with solid masonry external walls. Kragh and Wittchen [2] found that the external walls in multi-story residential buildings from the same period had an average-weighted U-value of 1.12 W/(m²·K). A large share of these buildings are protected as their aesthetic, historic and/or cultural values are considered worthy of preservation. This places several restrictions on exterior alterations, which often leaves internal insulation as the remaining option.
External insulation is usually regarded as the safer option, which provides effective protection from the external environment. In contrast, internal insulation is considered more risky and will leave the existing structure exposed [3]–[8]. Internal insulation reduces heat flow from the occupied zones to the exiting wall structure, which in turn becomes colder [3], [8]–[12] causing an increased risk of interstitial condensation [3], [4], [9], [13], [14]. In addition, the new insulation system also increases the diffusion resistance between existing wall and the occupied zones, which leads to reduced drying to the inside [9], [15]. The combination of these effects result in increased risk of moisture-induced damage such as mould growth [3]–[6], [9], [16], and wood decay [9], [16], [17], as the moisture levels increases in the critical locations within the wall structure. The traditional internal insulation system comprised of mineral wool and a vapour barrier [3]–[5], [12] have in many cases resulted in mould growth due to problems such as solar-driven vapour flow [3], [5], [18] and diffusion of warm moist air from the indoor environment out through the construction [3], [5]. The modern internal insulation systems have approached these issues differently. The diffusion-open capillary active systems allow the indoor moisture to diffuse in the outwards direction during the heating season, and then be redistributed back to the occupied zones by capillary actions as a mean to reduce the risk of mould growth inside the wall structure. Good hygrothermal performance for internal retrofitting solid masonry walls with diffusion-open capillary active systems have been observed in several studies including [6], [7], [15], [19]–[25], while other studies [26]–[29] found unacceptable relative humidity levels in the critical locations. The good performance in some of the aforementioned studies may be due to the combination of the diffusion-open capillary active systems with a low indoor moisture load and in some instances protection against Wind Driven Rain (WDR).

When dealing with internal insulation for solid masonry walls a number of factors may be of importance in terms of the hygrothermal performance in the critical locations such as the material properties of the brick and mortars used for the existing wall structure, thickness of the existing masonry wall and of the new internal insulation system, as well as the indoor moisture load. The results from a number of previous simulation studies [6], [17], [29]–[32] regarding the importance of
insulation thickness agree that increased thickness increases the risk of moisture-induced problems.

Findings in [17] suggests that the negative effects may be less pronounced for diffusion-open capillary active insulation systems, when compared with diffusion-tight systems with similar thermal resistance. The study by Nielsen et al. [33] suggested that the insulation thickness had only minor importance, and the risk of condensation from diffusion to the outside was a minor problem when compared to the quantity of moisture introduced through WDR. This conclusion is in agreement with statements by Straube et al. in [9] regarding the importance of WDR for internally insulated solid masonry walls. The simulation studies in [29], [34], [35] investigated the importance of masonry thickness and the results showed less critical Relative Humidity (RH) levels with increasing thickness.

In [29], [35] it was however pointed out that the capillary properties of the exterior bricks were of larger importance than the thickness of the existing masonry in terms of the amount of moisture reaching the critical locations. Limited information was found regarding the influence of the mortar properties on the performance of internal insulation.

A proposed measure to improve the hygrothermal conditions in the critical locations is to reduce the indoor moisture load [5], [9], [36], especially during the heating season. This would mean less potential for diffusion in the outwards direction and in turn less interstitial condensation. Previous field studies [15], [37] and simulation studies [14], [15], [29], [31], [38]–[40] have shown improved hygrothermal performance in the critical locations in the case of reduced indoor moisture load. The case studies in [7], [21], [23], [24] showed acceptable performance in the interface between the existing wall and the insulation system while subjected to a low indoor moisture load (studies were primarily using diffusion-open systems).

The purpose of this study was to assess the hygrothermal performance of four insulation systems for internal retrofitting in a temperate Nordic climate, using calibrated Heat And Mass Transfer (HAMT) simulations. The chosen insulation systems comprised three diffusion-open capillary active systems: 1) a composite material of polyurethane foam with calcium silicate channels in a grid of 40 mm by 40 mm ("PUR-CM"), 2) calcium silicate ("CaSi"), 3) lightweight autoclaved aerated concrete ("AAC"), as
well as 4) a phenolic resin foam insulation system with closed cell structure (“Phenolic”). One aim was to determine if the thickness of the existing masonry wall or of the new internal insulation was of considerable importance for the hygrothermal performance of internal insulation. The second aim was to test whether the use of bricks or mortars with considerably different material properties would highly affect the performance. The third aim was to determine if a controlled indoor climate with reduced moisture load would improve the performance of the internal insulation. Finally, the fourth aim was to examine if the insulation systems would be robust against the more severe weather conditions predicted for the future as a result of climate change [41].

2 Methods

2.1 Test stand description

The simulation models were created and calibrated using measurements from a large field experiment constructed at the Department of Civil Engineering of the Technical University of Denmark (DTU) on a test site in Kongens Lyngby, Denmark (55.79°N, 12.53°E) [42], [43]. The experimental setup consisted of several test walls constructed to resemble wall sections of Danish historic multi storey buildings from the period 1850-1930, both in terms of design and materials. The setup was designed to investigate the application of several diffusion-tight or capillary active diffusion-open internal insulation systems, applied to solid masonry walls with embedded wooden wall plate and beam ends.

The field experiment was carried out in two insulated reefer containers with the external dimensions (LxWxH): 12.2 m by 2.4 m by 2.9 m. Twenty-four 1 x 2 m cut-outs were made in the longitudinal side walls, in which solid masonry walls were constructed. The test walls were constructed as a 3-dimensional set-up comprising a 1987 mm by 948 mm by 358 mm (1½ stones thick with 10 mm interior rendering) solid masonry exterior wall, a 108 mm (½-stone) interior masonry wall with render on both sides, and a wooden floor construction made up of a 175 x 175 mm wooden beam end embedded 100...
mm into the masonry wall, supported by a 100 x 100 mm embedded wooden wall plate (Figure 1).
The floor construction was covered with 15 mm Oriented Strand Board (OSB). Inside the floor construction, 100 mm of mineral wool was used to emulate the clay-pugging layer traditionally installed between the floor beams. The experimental setup was constructed with special care and attention towards reduction of unintentional heat, air or moisture transport. The measures taken were: 1) Hygric and thermal decoupling through installing of a vapour barrier and mineral around each test wall; 2) sealing the exterior joints with mastic sealant in order to prevent rain intrusion; 3) Installation of gutters, and a flashing over each test wall against unintentional rain intrusion; and 4) The containers were raised 350 mm off the ground to prevent rain splash-up.

Figure 1 Test stand configuration: (a) Vertical section of a test wall. (b) Horizontal section through the 13th brick course. (c) Horizontal section through the 21st brick course. Source: Tommy Riviere Odgaard [42].
The indoor climate was kept at 20 °C and 60 % RH. No cooling or dehumidification were installed. Two fresh air fans were installed in each container to provide an air change rate of approximately 0.5 h⁻¹. For a Danish context this moisture load is fitting during the summer period, however during the winter period 60% RH is rather high. The Danish best practice guidelines [3] suggest RH values between 30-50% during winter. RH and temperature were logged every 10 minutes over 4 years (01-05-2015 to 01-05-2019) using digital HYT221 sensors installed and embedded in nine different locations in each test wall (Figure 1), and for the indoor and outdoor climates. The outdoor climate data (solar, wind and rain) were obtained from a climate station located 160 m south-west of the test site. South-west is the prevailing wind direction in Denmark, and the most critical in terms of WDR. The influence of WDR and high/low solar irradiation were examined by having sixteen of the twenty-four test walls facing south-west (237°), and eight to north-east (57°).

2.2 Simulation study

The simulations were carried out to study the hygrothermal performance of various alternative design scenarios for solid masonry walls with embedded wooden elements, fitted with diffusion-tight and capillary active diffusion-open insulation systems. The simulations were performed using the Delphin software [44], and the wall models were simulated for 4-years (May 1st 2015 to May 1st 2019) for the PUR-CM, CaSi and AAC systems and 1½ year for the phenolic foam system as this system was installed only on November 27th 2017. The simulation results were then post-processed with a mathematical mould-growth model.

2.2.1 Model configurations

In this paper, 1D and 2D HAMT models were created for seven of the twenty-four test walls applying the correct wall geometries and material data. The wall configurations and material data are listed in Table 1.
Table 1: Wall configurations used in the HAMT simulations. The insulation systems were applied internally to the existing wall configuration.

<table>
<thead>
<tr>
<th>No. of walls</th>
<th>Wall ID</th>
<th>Material layers</th>
<th>Density [kg/m³]</th>
<th>λ_dry [W/(m·K)]</th>
<th>μ_dry [·]</th>
<th>A_w [kg/(m²·s½)]</th>
<th>d [mm]</th>
<th>R [m²·K/W]</th>
<th>Z [m²·s·Pa/kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing wall</td>
<td></td>
<td>Yellow masonry brick*</td>
<td>1643</td>
<td>0.600</td>
<td>16.9</td>
<td>0.278</td>
<td>348</td>
<td>0.58</td>
<td>2.97E+10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7.7% lime mortar*</td>
<td>1243</td>
<td>0.440</td>
<td>22.4</td>
<td>0.390</td>
<td>10</td>
<td>0.02</td>
<td>1.13E+09</td>
</tr>
<tr>
<td></td>
<td><strong>Total: existing wall</strong></td>
<td></td>
<td><strong>0.60</strong></td>
<td><strong>3.08E+10</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 walls:</td>
<td>PUR-CM adhesive mortar</td>
<td></td>
<td>1313</td>
<td>0.497</td>
<td>18.8</td>
<td>0.005</td>
<td>10</td>
<td>0.03</td>
<td>9.47E+08</td>
</tr>
<tr>
<td></td>
<td>PUR-CM insulation</td>
<td></td>
<td>49</td>
<td>0.037</td>
<td>27</td>
<td>0.013</td>
<td>80</td>
<td>2.16</td>
<td>1.09E+10</td>
</tr>
<tr>
<td></td>
<td>PUR-CM render</td>
<td></td>
<td>1269</td>
<td>0.479</td>
<td>13.9</td>
<td>0.222</td>
<td>13</td>
<td>0.02</td>
<td>9.13E+08</td>
</tr>
<tr>
<td></td>
<td><strong>Total: PUR-CM system</strong></td>
<td></td>
<td><strong>2.21</strong></td>
<td><strong>1.28E+10</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 wall:</td>
<td>CaSi adhesive mortar*</td>
<td></td>
<td>1655</td>
<td>0.500</td>
<td>6.6</td>
<td>0.600</td>
<td>10</td>
<td>0.02</td>
<td>3.33E+08</td>
</tr>
<tr>
<td></td>
<td>CaSi insulation*</td>
<td></td>
<td>225</td>
<td>0.061</td>
<td>4.2</td>
<td>0.726</td>
<td>100</td>
<td>1.64</td>
<td>2.14E+09</td>
</tr>
<tr>
<td></td>
<td>CaSi adhesive mortar*</td>
<td></td>
<td>1655</td>
<td>0.500</td>
<td>6.6</td>
<td>0.600</td>
<td>8</td>
<td>0.02</td>
<td>2.67E+08</td>
</tr>
<tr>
<td></td>
<td><strong>Total: CaSi system</strong></td>
<td></td>
<td><strong>1.68</strong></td>
<td><strong>2.74E+09</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 walls:</td>
<td>Phenolic adhesive mortar¹</td>
<td></td>
<td>1516</td>
<td>0.500</td>
<td>41.4</td>
<td>0.006</td>
<td>5</td>
<td>0.01</td>
<td>1.05E+09</td>
</tr>
<tr>
<td></td>
<td>Glass fleece*</td>
<td></td>
<td>295</td>
<td>0.200</td>
<td>369</td>
<td>0.405</td>
<td>0.1</td>
<td>0.001</td>
<td>1.86E+08</td>
</tr>
<tr>
<td></td>
<td>Phenolic foam insulation*</td>
<td></td>
<td>35</td>
<td>0.020</td>
<td>114</td>
<td>0.009</td>
<td>100</td>
<td>5.00</td>
<td>5.76E+10</td>
</tr>
<tr>
<td></td>
<td>Aluminium foil</td>
<td></td>
<td>10000</td>
<td></td>
<td>1</td>
<td>5.05E+09</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Gypsum board</td>
<td></td>
<td>850</td>
<td>0.177</td>
<td>10</td>
<td>0.277</td>
<td>13</td>
<td>0.07</td>
<td>6.57E+08</td>
</tr>
<tr>
<td></td>
<td><strong>Total: Phenolic system</strong></td>
<td></td>
<td><strong>5.08</strong></td>
<td><strong>6.45E+10</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 walls:</td>
<td>AAC adhesive mortar*</td>
<td></td>
<td>830</td>
<td>0.155</td>
<td>13.0</td>
<td>0.003</td>
<td>8</td>
<td>0.05</td>
<td>5.25E+08</td>
</tr>
<tr>
<td></td>
<td>AAC insulation board*</td>
<td></td>
<td>99</td>
<td>0.044</td>
<td>3</td>
<td>0.006</td>
<td>100</td>
<td>2.27</td>
<td>1.52E+09</td>
</tr>
<tr>
<td></td>
<td>AAC adhesive mortar*</td>
<td></td>
<td>830</td>
<td>0.155</td>
<td>13</td>
<td>0.003</td>
<td>8</td>
<td>0.05</td>
<td>5.25E+08</td>
</tr>
<tr>
<td></td>
<td><strong>Total: AAC system</strong></td>
<td></td>
<td><strong>2.38</strong></td>
<td><strong>2.57E+09</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Materials used for the wooden floor structure

<table>
<thead>
<tr>
<th>Material</th>
<th>Density</th>
<th>Thickness</th>
<th>Cross-section</th>
<th>Water uptake</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pine wood (Longitudinal)</td>
<td>554</td>
<td>0.208</td>
<td>3.6</td>
<td>0.013</td>
</tr>
<tr>
<td>OSB board</td>
<td>630</td>
<td>0.130</td>
<td>280</td>
<td>0.002</td>
</tr>
</tbody>
</table>

Materials used in parameter variations

<table>
<thead>
<tr>
<th>Material</th>
<th>Density</th>
<th>Thickness</th>
<th>Cross-section</th>
<th>Water uptake</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brick Bernhard</td>
<td>2060</td>
<td>2</td>
<td>19</td>
<td>0.100</td>
</tr>
<tr>
<td>Old Building Brick Schloss Güterfelde</td>
<td>1532</td>
<td>0.383</td>
<td>10.4</td>
<td>0.218</td>
</tr>
<tr>
<td>Lime cement mortar, high CMT ratio</td>
<td>1878</td>
<td>0.803</td>
<td>36.9</td>
<td>0.036</td>
</tr>
<tr>
<td>Lime cement mortar, low CMT ratio</td>
<td>1739</td>
<td>1.050</td>
<td>28.3</td>
<td>0.495</td>
</tr>
</tbody>
</table>

*materials tested by TU Dresden, unmarked parameters were from the Delphin [44] material database or manufacturer information. +H denote exterior hydrophobisation. ¹Lambda was assumed based on similar products in the Delphin database.

The geometry for the 2D models were as illustrated in Figure 2; focusing on the transport through the wall itself and through the wooden floor construction. The 1D models focused on the transport through the wall itself, and were primarily used for the model calibrations which will be described in Section 2.2.3. The 1D models were simulated with a homogeneous masonry walls without mortar joints. The material properties were obtained from tests performed by the Technische Universität Dresden (TUD) in connection with the field experiment, and from the Delphin database. The exterior surface of the wall models was kept as bare brick, except for PUR-CM+H, Phenolic+H, and AAC+H which were simulated as hydrophobised. This was achieved by lowering the water uptake coefficient, $A_w$, by a factor 1000 for the outermost 10 mm of the existing masonry wall, similar to what was experimentally determined in [45]. The initial conditions (temperature and RH) measured in the 7 sensor locations were applied to the simulation models as shown in Figure 2.
Figure 2 Delphin screenshots of the simulations models: 1D wall detail of test wall PUR-CM+H (a); 2D wall detail of PUR-CM+H (b), and 2D beam end detail of Phenolic (c). P1-P7 represents the zones where the initial conditions (temperature and RH) for sensor points 1-7 were applied in the models.
Table 2 Boundary coefficients used for the calibrated models

<table>
<thead>
<tr>
<th>Boundary coefficients</th>
<th>CaSi</th>
<th>PUR-CM</th>
<th>PUR-CM+H</th>
<th>Phenolic</th>
<th>Phenolic+H</th>
<th>AAC</th>
<th>AAC+H</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground reflection (albedo) [-]</td>
<td>0.25*</td>
<td>0.25*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Short wave absorption [-]</td>
<td>0.7*</td>
<td></td>
<td>0.7*</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Long wave emission [-]</td>
<td>0.9*</td>
<td></td>
<td>0.9*</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rain exposure coefficient [-]</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>0.7</td>
<td></td>
</tr>
<tr>
<td>Int. heat exchange [W/(m²·K)]</td>
<td>5.0*</td>
<td></td>
<td>5.0*</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ext. heat exchange [W/(m²·K)]</td>
<td>13.2*</td>
<td></td>
<td>13.2*</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Int. vapour exchange [s/m]</td>
<td>3.0E-08*</td>
<td></td>
<td>3.0E-08*</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ext. vapour exchange [s/m]</td>
<td>2.0E-07*</td>
<td></td>
<td>2.0E-07*</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Value was applied to all seven models

2.2.2 Boundary conditions

The outdoor and indoor boundary conditions for the simulation models were obtained from the experimental study (measured outdoor and indoor temperature and RH are shown in Figure 3). For the atmospheric sky radiation, the Copenhagen Design Reference Year (DRY) data were used. The applied boundary coefficients are listed in Table 2. All the wall models were simulated facing south-west (237°).
Figure 3 Relative humidity and temperature for indoor and outdoor climates, used in the HAMT simulation

2.2.3 Model calibration

To obtain reliable HAMT models capable of approximating the hygrothermal conditions of the experimental test walls, the simulations were calibrated with respect to the experimental measurements. For the model calibration, the measured data were used for the outdoor and indoor climates, and for sensor locations 1-7. Assumptions were made for the boundary coefficients. The hygrothermal model calibration was carried out using 1D HAMT simulations (Points 1-4) and a Python automation script [46] which was set to vary and “crisscross” parameters. Prior to the automated calibration, a manual calibration was performed for the thermal properties of the seven “base” models to reduce the number of simulations in the automated calibration process.

Preliminary tests showed that the initial RH levels, rain exposure and shortwave radiation were the only parameters which had a significant influence on the simulation results. Consequently, the following parameters were crisscrossed by the Python automation script:

- Initial RH: in Point 1 (near the exterior surface), 2 (middle of masonry wall), 3 (in lime rendering at interface between masonry and insulation), and 4 (near the interior surface). The initial RH generally ranged ±15-20 %-point RH with intervals ranging from 0.05%-point RH (near 100%
RH) up to 5%-point RH. The range and interval setting varied between points and test walls based on the observed RH measurements from the experimental study.

- Rain exposure coefficient (range 0.7-1.3)
- Absorption coefficient for short wave radiation (range 0.5-0.7)

The Python automation script generated around 17000 1D HAMT simulations (between 1944 and 3456 variations for each of the seven base models).

Upon completion the script compared the simulated RH results in sensor points 1-4 to the measurement data to find the simulation models with the smallest area between the simulation curve and the measurement curve. The script then ranked the 20 best simulation models for each of the four sensors points (4 x 20 simulations), which were then exported to Excel for further manual calibration. The optimised parameters were then used as a basis for the 2D models, with some minor additional manual calibrations.

2.2.4 Model variations

After the model calibration several parameter variations were carried out for each of the wall models to investigate the effects of various alternative design scenarios. The parameter variations are described in Table 3. The properties for the alternative bricks and mortars are listed in the lower part of Table 1. The parameter variations D1A and D1B were simulated with an outdoor temperature dependent indoor humidity according to EN/ISO 13788:2013 class A and B [47], to investigate the effect of the indoor moisture load. The other parameter variations simulated with the measured indoor RH levels [42], [43].

Table 3 Parameter variations

<table>
<thead>
<tr>
<th>ID</th>
<th>Description</th>
</tr>
</thead>
</table>


A1 Replace air lime mortar with a mortar with high cement ratio (See material properties in Table 1)
A2 Replace air lime mortar with a mortar with low cement ratio (See material properties in Table 1)
A6 Replace air lime mortar with a mortar with high cement ratio, outermost 1 cm
A7 Replace air lime mortar with a mortar with low cement ratio, outermost 1 cm
A3 Replace yellow masonry brick with a low density brick (See material properties in Table 1)
A4 Replace yellow masonry brick with a high density brick (See material properties in Table 1)
B1 Reduce thickness of masonry wall to 228 mm (not done for beam end model)
B2 Increase thickness of masonry wall to 468 mm
B5 Increase thickness of masonry wall to 708 mm
B3 Reduce insulation thickness to R-value of 1.25 (K·m²/W)
B4 Increase insulation thickness to R-value of 7.50 (K·m²/W)
C1 CaSi system with hydrophobised exterior surface
D1A Indoor moisture load according to EN/ISO 13788:2013 Class A [47]
D1B Indoor moisture load according to EN/ISO 13788:2013 Class B [47]
D2 CaSi system with hydrophobised exterior surface + EN/ISO 13788:2013 (C1+D1)
E1 Climate data 2020-2050 Emission scenario A1B (Climate for culture) [48]*

*Note that 30-year simulation were carried out only for wall models with exterior hydrophobisation (PUR-CM+H, Phenolic+H, AAC+H and Casi+H).

Note that all parameter variations were simulated with the initial moisture content set according to the experimental measurements, and a second set of models set to 80% RH. This was done to investigate the effect of the built-in moisture on the individual parameter variations. The only exception was variation E1, which was simulated only with initial moisture set to 80% RH.

2.3 Mould growth risk

The widely used VTT mould-growth model by Hukka and Viitanen [49] was used for post-processing of simulation results to assess the hygrothermal conditions of the test walls over time, to produce a
theoretical prediction of the risk of mould growth. Focus was on the hygrothermal conditions in the
interface between the masonry wall and the insulation system (Point 3), and the embedded wooden
wall plate and beam end (Point 5 and 6).

The model produced the mould index (MI), ranging from 0 to 6, where 0 corresponds to no growth
and 6 to heavy growth (100% coverage). MI values 3-6 are within the visual range. The interface was
assumed to be “medium resistant” and with a decline factor set to “relatively low”, corresponding to
cement and plastic based materials. The embedded wooden elements were assumed to be “sensitive”
and with a decline factor set to “wood recession”. The predictions for the interface were initiated after
one year (on 01-05-2016 for PUR-CM, CaSi and AAC systems, and on 01-12-2018 for phenolic foam
system) to emulate the effect of the alkaline conditions during the initial drying out process for
systems using adhesive mortars, as suggested in [50].

3 Results

Supplementary plots including comparison between measured data and simulations, and datasets are
available in [46]. Plot abbreviations as listed in Section 2.2.1. The term “Calibrated” is used to describe
the outcome of the optimised simulation of the tested wall.

3.1 Simulation study

3.1.1 Model calibration

The automated calibration script reached rather small deviations between modelled and measured
RH levels for most of the wall models, see Figure 4 and [46]. However, a few models showed some 5-
10%-points RH lower than the measurements in the middle of the wall structure near the interface
between masonry and insulation system, e.g. as seen for the CaSi model in Figure 4a. This was despite
reaching a good match for the RH levels in points 1 (50 mm from the exterior surface) and 4 (in the
insulation, some 10-15 mm from the interior surface). Later calibration work for the 2D models
exhibited similar issues also for the wall plate sensor location (point 5), however to a less degree compared to near the interface. The large deviations between modelled and measured RH levels were seen to occur during periods when the experimental setup experienced RH levels near 100%. In the experimental setup these high RH levels were seen primarily for the test walls without exterior hydrophobisation. Lastly, it was seen that the automated calibration script was not able to reach a good match for the RH levels in all sensor locations in the Phenolic+H wall model despite performing approximately 3456 simulation variations, see Figure 4c.

Figure 4 Comparison between measured relative humidity from the container experiment and the calibrated Delphin models in the interface between wall and insulation: CaSi (a); PUR-CM+H (b); and Phenolic+H (c).
3.1.2 Effect of changing the mortar type

The simulations with different mortar types (no, low or high cement content) showed that changing the 7.7% air lime mortar to a low cement content mortar (1/11 part Portland cement and 10/11 part lime) reduced RH levels in the critical locations. In contrast, changing the air lime mortar to a high cement content mortar (½ part Portland cement and ½ part lime) increased RH levels (Figure 5). In addition, changing the mortar in the outermost 1 cm of the joints as done during renovation of joints had little to no effect on the RH levels in the critical locations. The simulations with reduced initial moisture content showed tendencies similar to the models with measured initial moisture (See [46]).

![Figure 5 Effect of varying mortar type, relative humidity in: Point 3 (interface) in PUR-CM+H (a), and Point 5 (wall plate) in CaSi (b). Note that the models with changed mortar type in the outermost 1 cm are on top of the calibrated model in the figure.](image)

3.1.3 Effect of changing the brick type

The simulations with varying brick types showed only minor differences between the three selected bricks, and no recurring tendencies that one of the bricks would perform better or worse in terms of the RH levels in the critical locations (see Figure 6a-b and [46]). The three bricks were generally within
5-8% RH points of each other. The only exception was the interface in the Phenolic+H wall model (Figure 6), where both the high and low density bricks showed considerably reduced RH levels compared to the yellow masonry brick. The simulations with reduced initial moisture showed only minor differences and no recurring tendencies (See [46]).

Figure 6 Effect of varying brick type, relative humidity in: Point 3 (interface) in PUR-CM (a), Point 5 (wall plate) in AAC+H (b), and Point 3 (interface) in Phenolic+H (c).

3.1.4 Effect of masonry thickness

The simulations with varying masonry thickness showed increased RH levels in the masonry/insulation interface with increasing thickness of the masonry brick wall (Figure 7a). However this tendency turned around after a hot and dry summer of 2018. The larger masonry thicknesses were observed to experience less seasonal variation compared to the thinner masonry thicknesses. The only exceptions
were the wall plate and beam end in the PUR-CM model, where the RH levels decreased with increasing masonry thickness (see [46]). The simulations with reduced initial moisture content did however show opposite tendencies compared to the simulations with measured initial moisture. In the case of reduced initial moisture RH decreased with increasing thickness (Figure 7b and [46]).

![Figure 7](image_url)

Figure 7 Effect of masonry thickness, relative humidity in Point 3 (interface) in: CaSi with measured initial moisture content (a), and CaSi with initial RH of 80% (b).

### 3.1.5 Effect of insulation thickness

The simulations with varying insulation thicknesses showed increased RH levels in the critical locations with increasing insulating thickness (Figure 8). Differences between thicknesses were observed to be larger for the highly diffusion-open insulation systems (CaSi and AAC) compared to the semi diffusion-open (PUR-CM) and diffusion-tight systems (Phenolic foam). The results for the critical locations showed smaller differences between insulation thicknesses in the wooden elements compared to the interface. Different results were seen for the models with the Phenolic foam system, which showed limited differences in all three locations (See [46]). Similar tendencies were seen between the simulations with measured and reduced initial moisture (See [46]).
Figure 8 Effect of insulation thickness, relative humidity in Point 3 (interface) in: AAC+H (open system) (a), and PUR-CM+H (semi-open) (b). R-values for the calibrated AAC+H and PUR-CM+H models were 2.27 and 2.16 K·m²/W respectively.

3.1.6 Effect of exterior hydrophobisation on Calcium Silicate

The simulations for the CaSi system with exterior hydrophobisation showed reduced RH levels in the critical locations (Figure 9). The RH levels were observed to be rather similar in the wall plate and beam end (See [46]). The simulations with reduced initial moisture also showed decreased RH levels in the interface due to the exterior hydrophobisation (See [46]).
3.1.7 Effect of indoor moisture load

The simulations with indoor humidity class A (normal occupancy) and B (high occupancy) according to [47] showed increased RH levels in the critical locations with increasing indoor moisture load (Figure 340a). During the initial 1-1½ years, the indoor moisture load had little to no effect on the RH levels. In addition, the effect of the indoor moisture load was seen to decrease with increasing diffusion resistance of the insulation system (Figure 10b), with the diffusion-tight phenolic foam system showing little to no change between the two indoor moisture loads. It was also observed that walls treated with exterior hydrophobisation experienced a larger reduction of the RH levels in critical locations due to reduced indoor moisture load compared to walls without (see [46]). The simulations with reduced initial moisture showed tendencies similar to the simulations using the measured initial moisture (See [46]). Note that the limited effect as a result of reduced indoor moisture during the initial 1-1½ years was seen to disappear in the case of reduced initial moisture.
3.1.8 Future climate predictions

The simulations carried out using the Climate for Culture [48] datasets with emission scenario A1B (Figure 11) showed that the models stabilised within the first five years. Hereafter were only minor deviations observed during certain individual years, and the RH levels would then fall back into place the subsequent year. The predictions for the interface between the masonry wall and insulation system showed less critical RH levels for the models with the PUR-CM and CaSi systems, but increasing RH levels for the models with the phenolic foam and AAC systems. The results showed reduced RH levels in the wall plate with increasing diffusion resistance of the insulation system, with the lowest RH levels seen for the phenolic foam system. The tendencies and RH levels for the beam ends were rather similar to those seen for the wall plates, see [46].

Figure 10 Effect of indoor moisture load (EN/ISO 13788 Class A and B), relative humidity in Point 3 (interface) for walls: CaSi (open) (a), and PUR-CM (semi-open) (b).
Figure 11 Relative humidity in Point 3 (interface) (a), and Point 5 (wall plate) (b); for models PUR-CM+H, Phenolic+H, AAC+H and CaSi+H – simulated with Climate for culture climate data for 2020-2050. Only the period 01-01-2020 to 01-01-2030 is presented graphically.

3.1.9 Mould-growth modelling

The mould growth predictions with the VTT model are listed in The diffusion-tight Phenolic+H was predicted to have the lowest overall mould growth risk in all three critical locations, while the PUR-CM model was predicted to have the worst overall risk in the interface and the CaSi model in the embedded wooden elements.

Table 4. Predictions were generally in line with the observations based on the RH levels, and tendencies were as follows:

- Mortar with high cement content increased the risk of mould growth, while mortar with low cement content reduced the risk. In addition, varying the mortar in the outermost 1 cm of the wall had little to no effect on the risk of mould growth in the critical locations.
- Varying the brick type had a rather modest influence on the risk of mould growth, and no general tendencies were observed.
- Increased risk of mould growth with increasing masonry thickness, as drying of the built-in moisture takes longer time.
- Increased risk of mould growth with increasing insulation thickness.
- Increased risk of mould growth with increasing indoor moisture load.
- The predictions for the simulations with climate for 2020-2050 showed low risk of mould growth in the wooden elements, but an unacceptable risk in the interface for models with the Phenolic and AAC systems. In addition, unacceptable maximum mould index values were observed in one or more locations in all insulation systems except for the CaSi system.
The risk of mould growth was predicted to be considerably higher in the wooden wall plate and beam end compared with the interface despite higher RH levels in the interface, due to the increased sensitivity of the wood products. The model predictions showed reduced risk for the simulation models with exterior hydrophobisation. The diffusion-tight Phenolic+H was predicted to have the lowest overall mould growth risk in all three critical locations, while the PUR-CM model was predicted to have the worst overall risk in the interface and the CaSi model in the embedded wooden elements.

Table 4 Modelled mould-growth predictions for the parameter variations

<table>
<thead>
<tr>
<th>ID</th>
<th>Parameter variation</th>
<th>Average VTT mould index, MI [-]</th>
<th>Max VTT mould index, MI [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>CaSi</td>
<td>PUR-CM</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Interface between existing wall and insulation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A1</td>
<td>Calibrated wall model</td>
<td>0.3</td>
<td>2.1</td>
</tr>
<tr>
<td></td>
<td>Mortar high CMT ratio</td>
<td>0.9</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>Mortar low CMT ratio</td>
<td>0.2</td>
<td>1.5</td>
</tr>
<tr>
<td>A6</td>
<td>Mortar high CMT ratio (1 cm)</td>
<td>0.3</td>
<td>2.1</td>
</tr>
<tr>
<td>A7</td>
<td>Mortar low CMT ratio (1 cm)</td>
<td>0.3</td>
<td>2.1</td>
</tr>
<tr>
<td>A3</td>
<td>Brick low density</td>
<td>0.7</td>
<td>2.1</td>
</tr>
<tr>
<td>A4</td>
<td>Brick high density</td>
<td>0.7</td>
<td>2.1</td>
</tr>
<tr>
<td>A1</td>
<td>Brick thickness 228 mm</td>
<td>0.3</td>
<td>1.3</td>
</tr>
<tr>
<td>B1</td>
<td>Brick thickness 468 mm</td>
<td>0.8</td>
<td>2.3</td>
</tr>
<tr>
<td>B2</td>
<td>Brick thickness 708 mm</td>
<td>2.1</td>
<td>2.6</td>
</tr>
<tr>
<td>B3</td>
<td>Insu. R-value 1.25 (K-m2/W)</td>
<td>0.2</td>
<td>2.0</td>
</tr>
<tr>
<td>B4</td>
<td>Insu. R-value 7.50 (K-m2/W)</td>
<td>2.2</td>
<td>2.1</td>
</tr>
<tr>
<td>C1</td>
<td>CaSi + Ext. hydrophobisation</td>
<td>0.6</td>
<td>1.2</td>
</tr>
<tr>
<td>D1A</td>
<td>Indoor RH ISO13788 Class A</td>
<td>0.1</td>
<td>2.1</td>
</tr>
<tr>
<td>D1B</td>
<td>Indoor RH ISO13788 Class B</td>
<td>0.1</td>
<td>2.1</td>
</tr>
<tr>
<td>D2</td>
<td>CaSi + Ext. hydrophobisation + ISO13788 (Case C1 + D1A)</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>E1</td>
<td>Climate data 2020-2050*</td>
<td>Average VTT mould index, MI [-]</td>
<td>Max VTT mould index, MI [-]</td>
</tr>
<tr>
<td>----</td>
<td>-------------------------</td>
<td>---------------------------------</td>
<td>-----------------------------</td>
</tr>
<tr>
<td></td>
<td>CaSi</td>
<td>PUR-CM</td>
<td>PUR-CMH</td>
</tr>
<tr>
<td>A1</td>
<td>Calibrated beam end model</td>
<td>4.8</td>
<td>3.7</td>
</tr>
<tr>
<td>A2</td>
<td>Mortar high CMT ratio</td>
<td>4.6</td>
<td>4.0</td>
</tr>
<tr>
<td>A3</td>
<td>Mortar low CMT ratio</td>
<td>4.4</td>
<td>2.5</td>
</tr>
<tr>
<td>A6</td>
<td>Mortar high CMT ratio (1 cm)</td>
<td>4.7</td>
<td>3.4</td>
</tr>
<tr>
<td>A7</td>
<td>Mortar low CMT ratio (1 cm)</td>
<td>4.7</td>
<td>3.5</td>
</tr>
<tr>
<td>A3</td>
<td>Brick low density</td>
<td>4.8</td>
<td>4.3</td>
</tr>
<tr>
<td>A4</td>
<td>Brick high density</td>
<td>4.7</td>
<td>4.0</td>
</tr>
<tr>
<td>B2</td>
<td>Brick thickness 468 mm</td>
<td>5.0</td>
<td>3.4</td>
</tr>
<tr>
<td>B5</td>
<td>Brick thickness 708 mm</td>
<td>5.0</td>
<td>2.7</td>
</tr>
<tr>
<td>B3</td>
<td>Insu. R-value 1.25 (K-m²/W)</td>
<td>4.7</td>
<td>3.5</td>
</tr>
<tr>
<td>B4</td>
<td>Insu. R-value 7.50 (K-m²/W)</td>
<td>5.5</td>
<td>4.8</td>
</tr>
<tr>
<td>C1</td>
<td>CaSi + Ext. hydrophobisation</td>
<td>4.2</td>
<td></td>
</tr>
<tr>
<td>D1A</td>
<td>Indoor RH ISO13788 Class A</td>
<td>4.7</td>
<td>3.5</td>
</tr>
<tr>
<td>D1B</td>
<td>Indoor RH ISO13788 Class B</td>
<td>4.8</td>
<td>3.6</td>
</tr>
<tr>
<td>D2</td>
<td>CaSi + Ext. hydrophobisation +</td>
<td>3.4</td>
<td></td>
</tr>
<tr>
<td>E1</td>
<td>Climate data 2020-2050*</td>
<td>0.1</td>
<td>0.0</td>
</tr>
</tbody>
</table>

### Embedded wooden beam end

<table>
<thead>
<tr>
<th>E1</th>
<th>Climate data 2020-2050*</th>
<th>Average VTT mould index, MI [-]</th>
<th>Max VTT mould index, MI [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CaSi</td>
<td>PUR-CM</td>
<td>PUR-CMH</td>
</tr>
<tr>
<td>A1</td>
<td>Calibrated beam end model</td>
<td>4.7</td>
<td>3.2</td>
</tr>
<tr>
<td>A2</td>
<td>Mortar high CMT ratio</td>
<td>4.5</td>
<td>3.7</td>
</tr>
<tr>
<td>A3</td>
<td>Mortar low CMT ratio</td>
<td>4.3</td>
<td>1.9</td>
</tr>
<tr>
<td>A6</td>
<td>Mortar high CMT ratio (1 cm)</td>
<td>4.6</td>
<td>2.9</td>
</tr>
<tr>
<td>A7</td>
<td>Mortar low CMT ratio (1 cm)</td>
<td>4.7</td>
<td>3.0</td>
</tr>
<tr>
<td>A3</td>
<td>Brick low density</td>
<td>4.7</td>
<td>4.0</td>
</tr>
<tr>
<td>A4</td>
<td>Brick high density</td>
<td>4.6</td>
<td>3.7</td>
</tr>
<tr>
<td>B2</td>
<td>Brick thickness 468 mm</td>
<td>4.9</td>
<td>2.9</td>
</tr>
</tbody>
</table>
Note that the listed average and maximum mould index values for the interface were calculated from the last three years (out of four) of simulation results for walls: PUR-CM+H, CaSi, PUR-CM, AAC and AAC+H. However, for walls Phenolic and Phenolic+H the values were calculated from the last 6 months (out of 1½ year), as the calibration datasets for these walls were shorter. For variation E1 “Climate data 2020-2050”, the mould risk was calculated from the last 29 years (out of 30). *Future climate simulations were performed with initial moisture set to 80% RH, and for the CaSi system the model was simulated with exterior hydrophobilisation.

4 Discussion

4.1 Model calibration:

The simulation models have all been calibrated with measurements, it is not a validation of the simulation, as this would require complete knowledge of material properties and boundary conditions. The issue regarding the calibrated simulation models exhibiting less RH fluctuation compared to the experimental measurements and often underestimating the RH levels seem to be a common issue for several simulation programs as found in [15], [51]–[57]. The review study by Busser et al. [58] similarly found that simulations often underestimate the adsorption processes and/or overestimate the desorption processes. This is probably due to the simulation software not accounting
for hysteresis, meaning that the RH-front moves faster in the experimental studies compared to what is modelled by the simulation programs, as shown by James et al. [59]. The authors pointed out several “biases” from within the experimental setup, measurement of boundary conditions, the simulation program, and material properties that are often forgotten or neglected when creating the simulation model, which could potentially close the gap between measured and simulated results. In contrast to these studies, Freudenberg et al. [60] obtained a good match between experimental measurements and simulation results using the Generic Optimization tool “GenOpt” for the model calibration. An alternative explanation for the discrepancies between the calibrated models and the measured data could be the measurement uncertainties of the digital sensors during periods with near 100% RH. The digital sensors used in the field study had an uncertainty of around 1.8%-point RH but the uncertainty increased when the RH levels were above 90%. It is possible that the “real” discrepancies between the calibrated models and the measured data may have been less than presented in this paper. The large discrepancies seen between the calibrated Phenolic+H wall model and measured data could perhaps be caused by incorrect installation of the phenolic foam system in the field experiment. It is possible that the desired tightness of the system was not achieved during installation, and so the system behaved more similarly to the diffusion-open systems. However, this does not correspond with the assumption in the simulation models that the installation was carried out perfectly. On the other hand, in the case that the problem was not related to the sensors but rather the simulation models, then the results suggesting that the Phenolic+H would be the best performing insulation systems would be questionable.

4.2 Effect of changing the mortar type:

The simulation results showed increased RH levels in critical locations for mortar with increased cement content and reduced RH levels for the mortar with reduced content, compared to the air lime mortar completely without cement. These tendencies were probably due to the higher water
absorption coefficient and liquid water conductivity for the low cement mortar and the air lime mortar
compared to the high cement mortar, but also due to a lower water vapour permeability with
increased cement content. With the high initial moisture content in the masonry wall (based on the
experimental measurements) the former two mortars would be able to transport liquid moisture away
more rapidly resulting in reduced RH levels compared to the less capillary and vapour permeable high
cement mortar. Due to the low water absorption coefficient, liquid water conductivity and vapour
permeability of the high cement mortar experienced only minor seasonal variations. The models with
the low cement mortar and air lime mortar did however experience larger seasonal variations with
reduced RH during the warm periods, and increased RH during the cold and rainy periods.

4.3 Effect of changing the brick type:

The limited differences between the three assessed bricks and no clear recurring tendencies for any
of the insulation systems could suggest that the brick type may not be of considerable importance in
relation to the hygrothermal performance in the context of the present setup. The comparison
between the high and low density bricks alone (excluding the yellow masonry brick) did however
suggest slightly increased RH levels for the high density brick, as this brick type had lower water
absorption coefficient and liquid water conductivity. The results corroborate with the simulations by
Kaczorek [32], but contradict the simulations by Mets et al. [29] who found increased RH levels using
bricks with higher liquid water conductivity. In addition, Mets et al. found the liquid water conductivity
to be more important than the water absorption coefficient in relation of the hygrothermal
performance, which corroborate present findings.

The large differences between brick types seen only for the Phenolic+H wall model in the interface
were probably related to the liquid water conductivity of the yellow masonry brick. The yellow
masonry brick deviated highly in terms of the liquid water conductivity and the simulated RH levels,
which could be due to a reduced liquid transport at lower moisture contents compared to the high
and low density bricks, see liquid water conductivity in [46].

4.4 Effect of masonry thickness:

The results for the simulations with high initial moisture content showed increased RH levels with
increasing masonry thickness, which contradict the findings in [4], [29], [34], [35]. In contrast, the
simulations with reduced initial moisture content showed reduced RH levels with increasing thickness,
in agreement with the other studies. The comparison between the two sets of simulations showed
that the wet initial conditions in masonry brick wall was the crucial factor causing the reverse
tendencies in relation to the masonry thickness. In the simulation with high initial moisture, the
thinner masonry thicknesses were observed to perform better in the critical locations as changes in
the outdoor climate were able to affect the moisture balance of nearly the entire masonry wall which
allowed the wall to dry out. In contrast, the larger masonry thicknesses were affected by the outdoor
climate only in the outermost part of the masonry wall while the innermost part maintained rather
stable conditions over the entire simulation period (less seasonal variation in the critical locations with
increasing wall thickness). In the simulation with reduced initial moisture, the larger masonry
thicknesses performed better as the increased thicknesses yielded more protection against the
outdoor climate affecting the moisture balance in the interface and embedded wood elements. This
resulted in less seasonal variation as compared to the thinner masonry thicknesses where WDR would
be more likely to reach the critical locations.

4.5 Effect of insulation thickness:

The simulations with varying insulation thickness indicate that increasing thickness worsens the
hygrothermal conditions in the critical locations as the added insulation thickness reduces
temperatures in the existing masonry further causing increased risk of interstitial condensation, and reduced drying to the inside due to the additional diffusion resistance. Both of these factors lead to increased risk of high moisture content in the wall structure. The present results are in agreement with findings in [5], [17], [29], [30], [32]. The sensitivity study by Nielsen et al. [33] did however conclude that the insulation thickness was of minor importance compared to parameters such as the orientation and WDR load. The comparison between the interface and embedded wooden elements suggests that the wall plate and beam end are less affected by the difference in insulation thickness. This is perhaps due to the locations of the wall plate and beam end, which were further away from the exterior surface of the insulation layer where the risk of interstitial condensation is the largest. In addition, these elements were also closer to the thermal bridge created by the floor structure, receiving more of the outgoing heat flow maintaining rather similar temperatures no matter the insulation thickness. It should however be noted that 2D simulations tend to overestimate the thermal bridge effect of said floor construction. It is therefore recommended to carry out 3D simulations in order to obtain the most realistic situation for the thermal bridge effect.

The comparison between insulation systems suggests that the diffusion resistance of the insulation system is of importance in terms of the hygrothermal performance. The semi diffusion-open (PUR-CM) and diffusion-tight (Phenolic foam) insulation systems experienced smaller differences in RH levels and seasonal variation with increasing insulation thickness compared to the highly diffusion-open systems (CaSi and AAC). Similar results were found in [29]. In addition, the study by Hansen et al. [30] showed only minor differences between insulation thicknesses with semi diffusion-open and diffusion-tight systems. These findings were probably caused by reduced drying to the inside with increasing diffusion resistance, and with sufficiently large thickness also the highly diffusion-open systems experienced limited seasonal variation.
4.6 Effect of exterior hydrophobisation on Calcium Silicate:

The simulations for the CaSi system indicate that a reduction of the water absorption of the outermost 10 mm of the masonry wall improved the hygrothermal performance of the insulation systems in all three sensor locations as driving rain intrusion was reduced considerably. This is in agreement with findings regarding the effect of hydrophobisation for the PUR-CM and AAC systems in the field study [42] and other studies dealing with exterior hydrophobisation [6], [61]–[63]. The simulations with reduced initial moisture content were in agreement with the simulations with measured initial moisture. However due to the low initial moisture content, the effect of the exterior hydrophobisation became visible already from the early part of the simulation period as compared to simulations with measured initial moisture content where the effect occurred after 1½ year due to the initial drying out.

Note that the reduction in the RH levels as a result of the exterior hydrophobisation was limited (some 5-10% point RH) compared to the diffusion-open AAC system in the experimental study (some 10-20% point RH) [42]. This is perhaps related to the observed differences between the calibrated model and the measurements for the CaSi system as mentioned in Section 3.1.1, which in turn reduced the potential benefit of the exterior hydrophobisation.

4.7 Effect of indoor moisture load:

The results indicate that a reduction of the indoor moisture load improved the hygrothermal conditions in the critical locations due to a reduced potential for diffuse to the outside as the indoor vapour pressure decreases, and so a reduced risk of interstitial condensation. The results support the findings in [15], [25], [29], [37], [39], [40]. The indoor moisture load was however found to be less important for the semi diffusion-open (PUR-CM) and diffusion-tight systems (Phenolic foam) compared to the highly diffusion-open insulation systems (CaSi and AAC), as smaller differences were observed between the two indoor moisture loads. This was probably because of the increased
diffusion resistance allowing less moisture from the indoor environment to pass through, so making
the indoor moisture load less important.

From the comparison between the simulations with measured and reduced initial moisture content it
was found that high initial moisture content in the masonry caused a delay on the effect of the reduced
indoor moisture load, as a limited effect of the indoor moisture load was observed during the initial 1
to 1½ years in the case of high initial moisture content. Similarly, the application of the exterior
hydrophobisation made the differences in indoor moisture load become visible early on as the
structure dried out faster.

4.8 Future climate predictions:

The results from the 30-year simulations suggests that the PUR-CM and CaSi systems combined with
exterior hydrophobisation (PUR-CM+H and CaSi+H) would be robust against the changing climate
conditions during 2020-2050 with emission scenario A1B. The AAC system combined with exterior
hydrophobisation (AAC+H) was however predicted to experience increased RH levels in all critical
locations compared to the PUR-CM and CaSi systems. For the Phenolic foam system combined with
exterior hydrophobisation (Phenolic+H) the wall model predicted sub-optimal performance against
the changing climate conditions in the interface between the masonry wall and the insulation, with
near 100% RH throughout most of the simulation periods. Robust performance was however
predicted for the Phenolic foam system in the embedded wooden elements. The tendencies observed
for the PUR-CM and AAC systems were in agreement with the experimental findings in [42]. The
observations for the Phenolic foam system in the interface were however contradictory to the
experimental findings [43], as progressively decreasing RH levels were found in the field study while
the modelling results predicted increased RH levels. The discrepancies could perhaps be related to the
problem with incorrect installation of the Phenolic foam system in the field study mentioned in Section 4.1.

In terms of reliability, exterior hydrophobisation has some limitations, which include issues with achieving good overall coverage and surface defects such as cracks and holes [3], [5], [64], [65]. In addition, there are several different water repellents available on the market and they may vary greatly in performance and service life [64]. Hees [66] stated that there is insufficient documentation regarding the application of water repellents, which prevents a sound evaluation of failures and successes with different treatments.

4.9 Initial moisture content:

The wet initial conditions used for the model calibrations were due to: 1) added moisture from the adhesive mortar used for the installation of the insulation system, and 2) the masonry walls being newly constructed and dried out for only one year prior to installation of the internal insulation. The test walls would certainly have been moister than what would be expected for historic buildings which would have had many decades to dry out. Some of the examined insulation systems and parameter variations would probably perform better in real case buildings compared to the experimental test walls used for the model calibration due to reduced initial moisture content. This highlights the importance of carrying out measurement campaigns over several years as the first few years of data may be unreliable due to the large impact of the initial conditions.

4.10 Wind driven rain

It should be noted that the WDR parameter is very hard to measure and model, and the use of hourly measurements as used in the present study could lead to the loss of peak rain events as rain exposure occurs irregularly. The loss of peak rain events could perhaps explain the more smooth RH
curves produced by the simulation models in comparison with the RH levels observed in the field measurements.

4.11 Risk of mould growth:

Regarding the reliability of mathematical mould growth models, previous studies [49], [67]–[71] indicate that the mathematical models are not able to precisely predict the extent of the mould growth infestation, but should instead be used to predict the likelihood of mould growth occurring in the structure or as a comparative tool to evaluate different design solutions. The experimental findings from the field study [42], [43] showed large discrepancies between on-site tests and model predictions. The application of the mould-growth model in this study was therefore used to assess the observed tendencies which include temperature, RH and time into the risk evaluation. The absolute MI values should be used with caution.

4.12 Summary:

Table 5 Summary of effect from model variations

<table>
<thead>
<tr>
<th>Variation</th>
<th>Impact</th>
<th>Best</th>
<th>Effect of initial moisture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mortar type</td>
<td>*</td>
<td>Low cement content</td>
<td>Insignificant</td>
</tr>
<tr>
<td>Mortar type, outermost 1 cm</td>
<td>-</td>
<td>No clear tendencies</td>
<td>Insignificant</td>
</tr>
<tr>
<td>Brick type</td>
<td>-</td>
<td>No clear tendencies</td>
<td>Insignificant</td>
</tr>
<tr>
<td>Wall thickness</td>
<td>**</td>
<td>Thickest</td>
<td>Important</td>
</tr>
<tr>
<td>Insulation thickness</td>
<td>**</td>
<td>Thinnest</td>
<td>Insignificant</td>
</tr>
<tr>
<td>Exterior hydrophobisation</td>
<td>*</td>
<td>With</td>
<td>Moderate(^1)</td>
</tr>
<tr>
<td>Indoor moisture load</td>
<td>*</td>
<td>Lowest</td>
<td>Moderate(^1)</td>
</tr>
</tbody>
</table>

Table denotations: - No impact; * small impact; ** larger impact. \(^1\)Effect occur during the initial 1-1½ years.
5 Conclusions

This paper presented a simulation study of solid masonry walls with embedded wooden elements and internal insulation. The models were calibrated using 2-4 years of measurements and obtained material properties. The hygrothermal performance of four insulation systems for internal retrofitting was assessed, and several parameter variations were carried out for the calibrated models. The results were post-processed with a mathematical mould-growth model to evaluate the risk of mould growth.

The following conclusions were drawn:

- Use of mortar with a high content of cement and low values on the water absorption coefficient, liquid water conductivity and vapour permeability for the joints between bricks was found to increase the RH levels in the critical locations, as less built-in moisture could dry out. Changing the outermost 1 cm of the mortar joints had little or no effect on the hygrothermal behaviour in the critical locations.

- In this study the brick type was found to be less important in relation to the hygrothermal performance, as only minor differences were observed between the three bricks and no clear tendencies were found.

- In terms of the effect of masonry thickness, the initial moisture content of the masonry wall was found to be of considerable importance. For a “wet” wall construction, the hygrothermal performance became worse with increased masonry thickness due to reduced drying of the built-in moisture. In contrast, with small initial moisture content an increased masonry thickness improved the performance due to increased protection against the outdoor environment.

- Increased insulation thickness was found to increase the RH levels in the critical locations as the additional insulation reduced the masonry temperatures and thereby caused less drying to the inside.
Exterior hydrophobisation was found to reduce the RH levels in the critical locations for the calcium silicate systems.

A reduction of the indoor moisture load was found to improve the hygrothermal conditions in the critical locations as it reduced the potential for diffusion in the outwards direction. However, due to the high initial moisture content the effect was reduced during the first 1-1½ year of the simulation period.

The 30-year simulations (2020-2050) suggest that the PUR-CM and CaSi systems in combination with exterior hydrophobisation would be a robust solution for the future climate conditions. In contrast, the AAC and Phenolic foam systems with exterior hydrophobisation could not be considered robust against the future climate conditions since unacceptable RH levels were observed in the critical interface between insulation and brick.

6  Acknowledgment

This research project was financially supported by Grundejernes Investeringsfond (The Landowners’ Investment Foundation), Realdania and the European Union’s Horizon 2020 research and innovation programme under grant agreement No 637268 – as part of the RIBuild project, which is gratefully acknowledged.

A special thanks to Ph.D. student Michele Libralato from Università degli Studi di Udine, Udine, Italy for the collaborative work on the automated calibration script.

7  References


of hygrothermal conditions at critical points in four cases of internally insulated historic solid


M. Ibrahim, E. Wurtz, P. Henry, P. Achard, and H. Sallee, “Hygrothermal performance of


