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Influence of hydrophobation and deliberate thermal bridge on hygrothermal conditions of internally insulated historic solid masonry walls with built-in wood

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Abstract

A large share of the Danish building stock contains historic multi-storey buildings. A considerable energy saving potential exists, achievable through thermal insulation of the façades. Previous research has elucidated problems regarding poor hygrothermal conditions when interior thermal insulation is applied to the façade, but examples exist with positive results.

Eight 1x2 m solid masonry test walls with wooden members were installed in an insulated container. The hygrothermal implication of applying 100 mm AAC as interior thermal insulation system was investigated with variations including use of hydrophobation and substitution of insulating material with a deliberate thermal bridge.

Relative humidity and temperature were monitored in the walls over 2 years in 10 measurement points. The amount of wind driven rain was monitored with rain gauges and calculated from climate station data. The indoor excess of humidity by volume corresponded to the highest indoor climate class for dwellings.

Damage models indicated risk of mould growth in the insulation/masonry interface, and risk of wooden decay in the wall plate for the reference and insulated case. Hydrophobation of the exterior surface in tempered cold climate reduced the overall relative humidity, although it increased during winter due to a reduced dry-out potential towards the outside.

Highlights

- Conditions behind thermal insulation reached critical values for mould growth.
- Conditions can be altered by hydrophobation and deliberate thermal bridges.
- Hydrophobation reduced relative humidity in summer, with rapid increase in winter.
- Relative humidity in built-in wood can be reduced by incorporating thermal bridge.
- Example of fit between wind driven rain model and measurements.

Keywords: field study, interior insulation, impregnation, thermal bridge, solid masonry, historic

1 Introduction

A large field study concerning eight solid masonry test walls with wooden members constructed in cut-out 1x2 m holes in an insulated container was setup up for experimentation with interior thermal insulation. The experiment was based on a large public interest in finding ways to reduce heating expenses and improving occupant comfort, while preserving the exterior expression of buildings that are renovated. The study focused on historic multi storey buildings from 1850-1950, an extensively investigated segment with similar characteristics during the period [1,2], which constitutes a large share of the Danish building stock [3]. The segment has been shown to have a large overall potential for reduction of heat loss [4,5], with considerable energy saving potential from applying thermal insulation to the solid masonry façade [6,7].

Previous research has focused on how to add interior thermal insulation to old masonry constructions and the performance of the insulation material [6,8–14]. Hygrothermal conditions in the original solid masonry wall are made worse when adding thermal insulation on the inside of constructions in cold climates, as the temperature of the original wall drops severely [15–17], increasing the risk of condensation at the original masonry surface behind the thermal insulation [15,18]. This effect, combined with reduced possibility for two-sided drying [17,19], result in increased moisture content of the wall at the cold side of the interior thermal insulation [13,16,18–23]. The degree to which the conditions are exacerbated is influenced by the interior and exterior boundary conditions, and increases with the thickness of insulation [24] and the amount of moisture entering the construction from both sides. The application of interior thermal insulation to an area limited to the spandrels below windows has been shown possible while avoiding damage from mould, wooden decay and frost [25], and may still achieve 40 % of the potential reduction in thermal transmittance with a full covering strategy, although it covers only 17 % of the surface [3].

Moisture influencing the interior boundary condition can be expressed as the indoor excess of moisture. The amount of moisture excess have been shown to vary within building style [26] and occupant behaviour and room type [27]. Based on this, an interior thermal insulation system must be able to cope with low and high indoor excess of moisture.

Moisture influencing the exterior boundary can be expressed as the outdoor humidity by volume and wind driven rain (WDR) affecting the façade. The WDR have been shown to have a large influence the average moisture level in internally insulated masonry walls [6,28], with increasing amount of water entering the façade as cracks and deficiencies of the exterior masonry surface are introduced [29].

Heaters and a humidifier were installed, ensuring a controlled level of indoor relative humidity and temperature. The outdoor wall surfaces were exposed to the local climate. The indoor and outdoor boundary conditions were monitored. Similar field tests were used in other European projects at BBRI, Belgium [23] and UCEEB, Czech Republic [30]. The paper presenting results from the field study at BBRI showed how the application of insulation to the interior surface of a solid masonry wall increased the moisture content in the masonry, especially for vapour tight insulation strategies, resulting in increased risk of hygrothermal damage. With diffusion open strategies, the influence from the inside environment was increased. Simulation based on the results obtained at BBRI showed that WDR had an important influence on the hygrothermal conditions in the wall. The paper presenting results from an ongoing field study at UCEEB was focusing on the conditions in the air gap around the embedded wooden beam end, showing that a high observed RH, and thereby risk of mould growth, could be reduced by sealing the air gap from the high influence of the inside environment towards the gap.

The measurements of boundary conditions at DTU included monitoring and calculation of WDR on the façade. An overview and comparison of state of the art WDR models has been performed by [31], comparing 2 semi-empirical models and a CFD model. We have in the

present study chosen to model WDR using the semi-empirical model originally developed by Lacy [32], and later extended by Straube [33,34].

As a mean to decrease the wetting of the masonry wall by WDR, hydrophobation of the exterior surface have been introduced by application of a water-repelling agent. The use of hydrophobation has shown to reduce the amount of moisture in walls and thereby also to decrease the thermal transmittance of the structures [24]. An experimental study was performed on the effect of applying the hydrophobizing agent "Funcosil FC" to bricks [35]. Engel et al. found that the application of agents with 10-60% active ingredient changed the properties regarding capillary saturation and water uptake, while water vapour diffusion resistance was nearly unchanged. The changes in properties were shown to highly influence the drying curves of brick, lowering the rate of drying/return transport of water with increasing active ingredient in the hydrophobizing agent.

The aim of this paper is to present an investigation of how the hygrothermal conditions in the wall system are affected by the application of thermal insulation on the interior surface; the influence from applying a hydrophobic façade treatment to the exterior masonry surface and by applying a deliberate thermal bridge next to embedded wooden elements.

The field study is based on measured hygrothermal conditions in four identical solid masonry walls with built in wooden elements, with the same base thermal insulation system on the interior side. The interaction between the interior thermal insulation system and two means have been investigated. The first mean was the application of a hydrophobizing agent to the exterior masonry surface. The second mean concerned replacing a share of thermal insulation material with a deliberate thermal bridge. The hygrothermal conditions were continuously measured during a monitoring period of 2 years.

2 Method: Description of field study set-up and measured data

2.1 The base: Perforated container with solid masonry walls

A large-scale field study was built at the field test site of the Department of Civil Engineering at the Technical University of Denmark (DTU) in Kongens Lyngby, Denmark (55.79°N, 12.53°E). The set-up was constructed as an adjusted sample of the traditional Danish multi storey building from the period 1850 to 1930. The main idea for the field study was based on the use of a castoff 40 feet insulated container, similar to two previous field studies at DTU [36]. The façade of the field study was oriented towards the critical direction in Denmark, south-west, based on dominating winds from west [6,37], yielding critical wind driven rain, combined with solar exposure from the south, resulting in potential transport of moisture towards the indoor climate. The exact angle of the façade can be seen from aerial photos illustrated in Figure 1, showing an actual direction of west-southwest, with a compass angle of 237°. Holes of 1 m width x 2 m height were cut in the facade for the construction of 8 identical base walls for experimentation with thermal insulation.

Figure 1 Ortofoto of field study at the test site of the Technical University of Denmark. This paper focus on results from container D4. Photo courtesy of Maps from COWI.

Construction of the masonry walls were finished on September 18th 2014, from when a forced dry-out period started. The dry-out was performed to remove the moisture induced from the building process, by heating up the indoor climate to 40-50 °C with two 2000 W calorifères, resulting in an indoor relative humidity in the range 10-30%. The dry-out conditions from the external side were achieved by establishing a tent, open at both ends, and apply heat with one 9000W calorifère in the period December 2014 to April 2015. The walls were assessed as dried out based on Troxler measurements at the interior side of container C3, showing counts similar to 1 (+/- 0.5) weight-% moisture in masonry, and measured RH under saturation in the embedded digital RH/T sensor points in the masonry. The thermal insulation systems were installed on February 24th and 25th, 2015, with the different means to change the hygrothermal conditions illustrated in Figure 3. As mentioned later in Section 3.3, the first year of relative humidity measurements was used as a stabilization year. It must be acknowledged that the applied forced dry-out have changed the initial carbonation process, as high temperature and low relative humidity ($RH < 30\%$) have previously shown to reduce the speed of the carbonation process of the used lime mortar [38]. The carbonation of the masonry walls during the first period is therefore limited, whereas carbonation of the outmost layers, which provide the protection against wind driven rain, is expected sufficient during the first year of stabilization. No additional CO_2 have been applied to the experiment, even though literature show promising results [39].

Figure 2 Overview of investigated wall/insulation compositions in container D4. The meaning of the text next to the walls are described in Section 2.1.2. Results from the un-shaded Walls 2, 3, 5 and 6 are investigated in this paper.

A humidifier to keep the chosen indoor moisture level was started on May 21st 2015, marking the beginning of the experiment. Data for use in the present paper were drawn on May 1st, 2017, for the 2-year period 01-05-2015 until 01-05-2017. In order to stress the experiment, the set point of the humidifier was set to 70% relative humidity in the first period, May until August 2015, then adjusted to 60% relative humidity for the rest of the period which can be considered as a high but not un-realistic value for Danish dwellings in the winter. This set point has traditionally been used as indoor climate conditions for building envelope experiments in Denmark. Yet to be published research from Hansen and Møller, altering the previously found transformation of indoor excess of moisture for indoor experiments [40] to DRY data [37], show that the highest climate class 3 for dwellings [41,42] in Denmark correspond to minimum 60 % RH during the year.

2.1.1 Setup of base walls in field study

The 8 identical base walls were designed to resemble the intersection of two façade wall columns with a room dividing solid interior wall at the highest floor and a floor structure, including a wooden beam, of a characteristic Danish multi-storey building. Illustrations of the base walls can be seen in Figure 3 (a-c). The horizontal design of the base walls had a width of 948 mm, equal to 4 stones of brick, and a thickness of 358 mm, 1½ stones, with a layer of rendering on the inside. The rendering and mortar joints were made of the same material: lime mortar. The masonry walls were constructed as massive brick walls in a characteristic cross bond with lime mortar joints by professional masons. An interior wall was built with a thickness of 128 mm, ½ stone, with a layer of rendering on both sides. The vertical design of the base walls had a height of 1987 mm, 30 courses, with a floor structure having a top point at the vertical middle of the wall. The floor structure consisted of a 100 x 100 mm wall plate with a 175 x 175 mm wooden beam resting on top of this. 15 mm OSB boards on all sides except towards the interior wall encapsulated the wooden beam. 100 mm of mineral wool was placed in the OSB board enclosure to emulate a pugging layer. The wooden beam/OSB board construction was constructed to the left of the interior wall, while the space on the right side was kept empty, also for walls where insulation systems were applied.

Figure 3 Illustration of wall composition and location of measurement points in Wall 6. Masonry, rendering, wooden elements and insulation on boundaries are identical for all walls. Installed thermal insulation on Wall 2 & 3 are equivalent, but with insulation in front of wall plate instead of AAC. Wall 5 is un-insulated. (a) show a vertical cut in the wooden beam, (b) & (c) show courses with measuring equipment. Data from the measurement points 1, 2, 3, 4, 5, 6 & 10 are investigated in this paper. Pictures from construction of experiment can be seen in [43].

2.1.2 Insulation systems and surface treatments

All thermal insulation systems used in the field study were based on a system of lightweight AAC. The system was installed with variations, as it can be seen in Figure 2. The notation next to each wall describe the installed interior insulation system and internal/external surface, specific materials are described in Section 2.1.3. The used descriptions in Figure 2 denote:

- First line: Description of the interior surface.
 - Reference wall: No insulation installed, identical to base walls.
 - Interior insulation: Diffusion open thermal insulation system based on lightweight AAC.
 - Interior insulation + therm. bridge: Diffusion open thermal insulation system based on lightweight AAC, supplemented with a 100 x 200 mm AAC with higher density in the top 200 mm underneath the floor structure. This block was implemented to create an intentional thermal bridge, meant to protect the wall plate and beam behind. A detail drawing of the system can be seen in Figure 3(a).
- Second line: Description of the exterior surface.
 - Rendering: Rendered surface of the base wall.
 - Diffusion-open paint: A silicate based interior paint.
- Third line: Description of the exterior surface.
 - Bare brick: Bare brick surface, identical to the base wall.
 - Hydrophobized bare brick: Hydrophobic facade treatment of the bare brick masonry. The hydrophobizing agent was rolled onto the exterior masonry surface in April 2015. The exterior surface of the experiment was protected against rain with a tent at the time of application, and the surface and environment temperatures were sufficient according to instructions, backed up by a calorifere in the tent relating to the forced dry-out procedure.

2.1.3 Materials in field study

Material samples were sent to the Technische Universität Dresden (TUD) for characterization in their material laboratory, as part of a collaboration between DTU and TUD.

The materials used in this study, with parameters measured at TUD if not stated otherwise, can be seen in Table 1.

Name	Density [kg/m ³]	λ_{dry} [W/(m ² ·K)]	μ_{dry} [-]	A_w [kg/(m ² ·s ^{0.5})]
Yellow soft-moulded brick from Helligsø Teglværk	1640	0.60	16.91	0.278
7.7% lime adjusted mortar (air lime), grain size 0-4mm from Wewers A/S designed to resemble mortar used in historic buildings	160	0.08	18.75	0.764
Ytong Multipor Interior Mineral Insulation Boards	100	0.04	6.73	0.006
Ytong Multipor Light Mortar	830	0.16	-	0.003
Ytong massive block	340*	0.08*	5/10*	
Wall plates and wooden beams of Pomeranian pine wood.				
OSB board				
Ytong Multipor Silicate Interior Paint				
Remmers Funcosil FC (Concentration = ~40% w/w).				

Table 1 Hygrothermal properties for materials used in field study. * denote material properties stated by producer, non-marked parameters are measured at TUD.

2.2 Measuring equipment

Two measurement systems were installed in the field study, one based on digital sensors logging every 10 minutes and one based on manual measurements of electrical resistance of wooden sensors. This paper will mainly present results from the digital system. Results from the system based on electrical resistance is used for validation of results from the digital system.

Wind driven rain sensors with built-in data loggers were installed on the external south-west oriented wall of container C3 and D4. The placement of the containers can be seen in Figure 1.

2.2.1 Placement of measuring equipment

The measurement points investigated in present paper are described in the following bullet list, with positions illustrated in Figure 3 (a-c).

- Point 1: Digital RH/T sensor, mounted in brick, near exterior masonry surface.
- Point 2: Digital RH/T sensor, mounted in brick, in middle of masonry wall.
- Point 3: Digital RH/T sensor, mounted on interior masonry surface, covered by rendering.
- Point 4: Digital RH/T sensor, mounted in 10 mm deep cut channel in the interior insulation, covered with the mortar belonging to the insulation system.
- Point 5: Digital RH/T sensor and wooden dowel for electrical resistance measurement, mounted in wall plate from the bottom and sealed with silicone.
- Point 6: Digital RH/T sensor, mounted in wooden beam and sealed with silicone. Hole drilled horizontally from opposite side of the interior wall, with measurement point in the beam centre.
- Point 10: Digital RH/T sensor exclusively in Wall 6 & 7. Mounted in 10 mm deep cut channel in the AAC thermal bridge, covered with the mortar belonging to the insulation system.

2.2.2 Setup of digital RH/T sensor system

The system was based on Arduino boards, reading measurements from sensors connected to the same main cable and logging the values to a computer. The digital RH/T sensors used in the experiment were constructed from modules and cables from two different companies, both mentioned in the acknowledgements. The module to sensor cable connection was protected using adhesive shrink tubing, covering the module and sensor cable, but uncovered at the sensing area of the module, a process which may be followed in [43]. The resulting sensor dimensions are approximately (b x h x l) = 15 x 10 x 60 mm. The producer of the sensor module stated an operating range of 0-100 % RH, with an accuracy of +/- 1.8 % RH in the range 0-90 % RH. Accuracy in the range > 90 % RH was not accessed as important for the experiment, as this is above the limits for mould growth and wooden decay. The long-term drift of the modules was stated as < 0.5 % RH/year.

2.2.2.1 Calibration and post processing of digital RH

Each individual sensor was calibration at the start of the project. This was done after protecting the module/sensor cable connection with adhesive shrink tubing, prior to installing the sensor in the field study.

The measured relative humidity for each sensor was calibrated with four saturated salt solutions in ad- and desorption. The calibration was performed in a vapour tight box with an internal fan for ensuring homogeneity of the air. The relative humidity at each step was validated using a Rotronic Hygrometer A2, calibrated prior to the process over certified Rotronic ampoules.

The following saturated salt solutions were used for the calibration, with the resulting relative humidity in brackets: Potassium Carbonate K_2CO_3 (44%); Sodium Chloride NaCl (75%); Potassium Nitrate KNO_3 (93%); Potassium Sulfate K_2SO_4 (97%). Focus was on relative

humidity from 75% and up, as the intention was to investigate if conditions amenable to mould growth and decay conditions would be met [44–46]. The sensors were exposed to each saturated salt solution until steady conditions were achieved, before changing to next salt solution. In the end, a unique linear trend line was fitted to the measurements from each sensor, yielding an equation to convert from measured relative humidity to real relative humidity. Sensors with diverging calibration equations or outliers were discarded.

The individual calibration values of each sensor were applied and results were truncated to be between 0.00 and 99.99 % RH. Corrupted data with unrealistic values and outliers from failing sensors and power cuts were removed.

The resulting unique calibration equations had the form illustrated in Equation (1), and an example of some calibration values for the sensors monitoring the environment can be seen in the following bullet list.

$$RH_{calibrated} = RH_{measured} \cdot a_{calibration} + b_{calibration} \quad (1)$$

- > $RH_{calib-inside_{NW}} = RH_{meas-inside_{NW}} \cdot 0.995 + 1.739$
- > $RH_{calib-inside_{SE}} = RH_{meas-inside_{SE}} \cdot 0.986 + 1.177$
- > $RH_{calib-outside} = RH_{meas-outside} \cdot 0.989 + 0.079$

2.3 Climate conditions

2.3.1 Indoor climate conditions

The indoor climate was maintained by installing two heaters and one humidifier, while cooling and dehumidification were not carried out. Indoor set points of 20 °C and 60 % relative humidity were maintained by two 1000 W electric convectors and a "Brune B125" humidifier, supplied with demineralized water. Sensors similar to those used in the walls, hanging from the roof in each end of the field study, 20 cm from the roof, 2 meters from the ends, monitored the indoor climate. The output from the two indoor climate sensors was averaged. Air change in the field study was ensured via a fresh-air valve in the north-west end, and an exhaust fan in the southeast end, with a capacity of maintaining an air change of 0.5/h. The fan was in operation outside of the heating season to reduce humidity and temperature in the field study. A circulation fan was installed in the southeast corner of the field study to ensure constant air movement.

2.3.2 Outdoor climate conditions

The exterior wall surfaces were exposed to the local climate. Rain run-off from the roof was ensured not to affect the walls by installing a gutter. The nearest building was a similar field study located in the south-west direction, at a distance of 6.7 meter and a height of 3.1 meter. Located straight west in a distance of 7.6 meter was another building, with a height of 6.5 meter. The local temperature and relative humidity were monitored by one sensor similar to those used in the walls, placed behind a wooden cladding under the gutter between Wall 4 & 5. The climate of the local area was monitored by DTU's climate station [47], situated 160 m to the west-southwest, at an altitude 16 m above the field study.

2.3.2.1 Wind driven rain

Three wind driven rain (WDR) gauges were installed, one between Wall 4 and 5, two on nearby container C3 (see Figure 1), same direction as on container D4 and opposite by 180°. The gauges are based on a commercial vertical rain gauge mentioned in the acknowledgements, mounted in custom-built frames to monitor horizontal rain. Considerations defining the design may be seen in [48]. The frame was constructed from acrylic glass (PMMA) with a raised border of 10 mm around the 300 x 300 mm collector area. The WDR hitting the vertical collection area drained into the closed tipping bucket, logging time and tips. The rain gauges were calibrated before installation, to define the amount of liquid per tip. All rain gauges were in function from June 6th, 2016.

Figure 4 Picture (a) and drawings (b-c) of Wind Driven Rain (WDR) gauge developed and used for the field study. The bottom white bucket with integrated tipping gauge and datalogger is a commercial product for logging vertical rain. Drawings produced by Linatex A/S.

The experiment was in operation 13 months earlier than the rain gauges were installed. To obtain information regarding the WDR influencing the façade before June 2016 and during errors on the WDR gauges, the WDR model methodology of [34] was applied to the data from the weather station in Equation (2).

The transformation from horizontal rain in the free wind field to rain impinging on the specific facade is based on a multiplication with building and environment dependent factors [34]. The multiplied factors in this project are determined from fitting the model to measured WDR. The resulting effect of the fitted $Factor_b = 0.49$, can be seen later under presentation of boundary conditions in Section 3.2, Figure 5 and in the WDR discussion in Section 3.4, Figure 14 and Figure 15.

$$r_{vb} = Factor_b \cdot r_v = Factor_b \cdot DRF \cdot V(z) \cdot \cos(\theta) \cdot r_h \quad (2)$$

where: $V(z)$ is wind speed at height of interest, defined as $V(z) = V_{10} * \left(\frac{z}{10}\right)^{\alpha_v}$, V_{10} is standard wind speed from weather station [m/s], z = height of interest [WDR gauge = 1.75 m], α_v = exposure coefficient (0.25 for suburban area [34]), θ = angle between wind direction and wall surface [°], r_h = horizontal rain [mm or l/m²].

The DRF (Driving Rain Factor) defines the wind speed/raindrop fall speed interaction. The DRF is used in multiple WDR models, tending to be a fixed standard parameter defined from average conditions, varying from 0.20 to 0.25. But as raindrop fall speed changes with drop size, DRF can vary in the range from 0.15 to 0.50 when drizzles or cloudbursts are studied [34].

DRF has been calculated for 1 minute data steps based on the methodology described by Straube [33]. The median relative frequency of raindrop size is determined from the rain intensity [49]. The median raindrop size is used to determine the raindrop terminal fall speed [50]. Finally, DRF is determined as the reciprocal of the fall speed [33,34] resulting in the varying DRF over rain intensity. Calculation of varying DRF has been incorporated in an Excel sheet with embedded VBA scripts, available here [51].

2.4 Implementation of damage modelling

The results of the field study show how the different insulation systems have an influence on the measured relative humidity and temperature. While damage models have previously been shown unable to precisely predict mould growth in constructions, for example by Møller et al. showing no mould activity during constant critical conditions for mould growth in a laboratory experiment [52], the models are still valuable tools when assessing the significance of combined hygrothermal conditions. The models have been used to transform the combination of non-smoothened measurements and exposure time into theoretical risk of damage with two different damage models, with the purpose of comparing the different insulation strategies to the measurements in the reference wall. The damage models are only presented briefly and the sections mainly serve for defining the used parameters, as we will refer to another paper where we gave an in-depth presentation and discussion of the implemented damage models [25], while other researchers have done broader review and discussion of more damage models [53–55].

2.4.1 Mould modelling

The risk of mould occurring on the interior surface and behind the interior insulation is modelled based on the VTT model [44,56,57]. The output of the model is a mould index, M , ranging between 0 and 6, with each integer defining a state of mould growth [44]. The measurement points were modelled as non-wood, medium resistant materials, using a limit curve as suggested in [25].

2.4.2 Decay modelling

The risk of wooden decay is evaluated based on the extended VTT model [46]. The model has two outputs: "Activation process", a , which is the state of the decay process, and "irreversible wooden mass loss", ML , which increases when $a = 1$. The alpha value in all calculations have been started at $a = 1$.

3 Results and discussion

The results and discussion have been combined in the present paper, to simplify the presentation of results and allow for placement of discussion near plots of measures data. The results presented in this paper can be seen in Figure 5 - Figure 10, Figure 12 and Figure 13. The presented results are obtained from a 2-year monitoring period: 01-05-2015 until 01-05-2017.

Raw relative humidity data will not be presented, measurements from the digital sensors have been adjusted based on unique sensor calibration equations and filtering settings described in Section 2.2.2.1. The presented results are based on smoothened 96-hour running average values, in order to communicate the trends in the field study.

The results and discussion is composed from the following subsections:

- A consistent plot setup used throughout the paper.
- The boundary conditions of the field study.
- Evaluation of the measured temperature, relative humidity and appropriate damage models of the different points. The sensor points are evaluated based on measured temperature and relative humidity, as these values are used when evaluating the implemented mould and decay models described in Section 2.4.1 and 2.4.2 respectively. The outputs of the mould model is included in plots for the interior surface and the interior masonry surface behind insulation (abbreviated: masonry/insulation interface). The outputs of the wooden decay modelling is included in plots for wall plate and wooden beam end.
- A study into the effect of the hydrophobic treatment by comparison of the non-smoothened relative humidity to wind driven rain (WDR).

The starting point for the moisture conditions deviated for the four walls. By inspection of measurements from the masonry walls in Figure 13 it is observed that the moisture conditions vary and do not stabilize until the 2nd summer, in May 2016. Determination of moisture stabilization in the 2nd summer is based on similar values in May of 2016 and 2017. All measurements have been included, but measurements prior to May 2016 are marked with "stabilization period" and the discussion of the results are based on the period after stabilization. The thermal conditions stabilize faster, showing stable results as of August 2015. The damage models: wooden decay mass loss and mould index have been calculated with starting point at the time of stabilisation.

3.1 Plot setup, consistent line colour, style and markers used throughout paper

The figures throughout the paper are consistently marked from line colour, style or marker, as illustrated in Table 2.

- The specific line colour indicate the wall number or specific WDR station.
- The line style indicate the variable.
- The line marker indicate the measuring point or daily sum of WDR.

The clear distinction in line format are implemented to allow for identification of the wall composition, measurement point and variable without need to consult the legend.

Line colour	Line style	Line marker
Blue = W2: Ins.	— Solid = RH	1 no. 1 = P1: Ext. masonry surf.
Red = W3: Ins. & hydr.	--- Dot Squared = Θ	2 no. 2 = P2: Middle of masonry wall
Green = W5: Ref. wall	— · Long Dash Dot Dot = M	□ Square = P3: Int. masonry surf.
Black = W6: Ins., hydr. & therm. bridge	- - Dash = α	◇ Diamond = P4: Inside of ins.
Pink = Outdoor climate	— · Long Dash = ML	△ Triangle = P5: Wooden lath
Brown = Indoor climate	— Solid, thick = r_{vb}	○ Circle = P6: Wooden beam end
Dark blue = r_{vb} , calculated, DTU climate station		+ Plus = P10: Surf. of therm. bridge
Turquoise = r_{vb} , measurement, Container D4		× Star = r_{vb} , daily sum
Lime = r_{vb} , measurement, Container C3		

Table 2 Description of consistent line colour, style and markers used in all plots in present paper. The different wall compositions are illustrated in Figure 2. The location of measurement points are illustrated in Figure 3.

The date stamps in all figures are defined as "dd-mm-yy". The position of the line markers are defined based on the position of the date stamps on the x-axis.

3.2 Boundary conditions in field study

Measured boundary conditions can be seen in Figure 5, where the indoor conditions are averages of two measurements: one from each end of the field study. Horizontal rain measurements from DTU's climate station [47] were fully operational as of 2015.09.05. WDR deposition on vertical building façade angled 237° from north (r_{vb}) have been calculated from this point in time and onwards, illustrated with a thick dark blue line. Measured r_{vb} is illustrated with thick turquoise and lime colour lines for container D4 and C3 respectively. Periods with fault on the individual WDR gauges are illustrated by removing the line. The cumulative values for faulty sensors follow the increase of the calculated WDR based on DTU's climate station.

Figure 5 Measured in- and outdoor boundary conditions in field study. The temperature and relative humidity are measured inside and just outside the field study. The WDR data, expressed as r_{vb} values, are measured at the exterior surface of the field study, and calculated from logged values at a nearby climate station. The measured r_{vb} follow the equivalent calculated values in periods with missing data.

The indoor set points were: Temperature = 20 °C and relative humidity = 70 % in the first 3 months, 60 % during the remaining period. As dehumidifier and cooling units were not fitted, fluctuations were possible in periods with impact from high outdoor temperature/solar radiation and humidity.

During the monitoring period, the water tank for the humidifier ran out two times, resulting in decreased indoor relative humidity in the periods: 2016.01.02 until 2016.01.26 and 2016.10.30 until 2016.12.07.

The indoor excess of moisture in the field study was assessed based on humidity classes [41,42]. The resulting humidity class within the heating season was class 3 "Buildings with unknown occupancy" [41], defined as an indoor excess of moisture of 6 g/m³ at 0 °C, falling linearly to 0.75 g/m³ at 20 °C.

3.3 Measured relative humidity and temperature, combined with damage model calculations

The following results and discussions are split into various points of interest, being either specific sensor points or locations on the wall (e.g. the interior surface, which will have varying sensor point number depending if insulation have been applied or not).

3.3.1 Temperatures from digital RH/T sensors. Two graphs, additional in dataset.

Investigation of the changed temperatures when installing interior thermal insulation is not the purpose of the present paper. The temperatures are however a key component to understand the magnitude of the measured relative humidity. The two graphs included in this subsection are examples of the material supplied in [58], including 30 temperature plots for additional combinations of walls/sensor points, the full monitoring period and two winter periods. The discussion of the temperatures in the current section are based on investigations into the full dataset, based on graphs and data in .csv format [58], analysing various combinations of sensor points and walls individually.

The graphs included as examples of the presented walls/points and periods can be seen in Figure 6 and Figure 7. Figure 6 include measurements from sensor Points 3-6 and 10 in the insulated and hydrophobized Wall 6 with a deliberate AAC thermal bridge next to the wall plate in the full monitoring period. Figure 7 include measurements in Point 5, the wall plate, in all analysed walls during the first winter period.

Figure 6 Measured Θ throughout monitoring period. Measurement from sensor points in Wall 6: Insulated, hydrophobized and with deliberate thermal bridge. The measurements in Points 3, 5 and 6 are difficult to distinguish, but follow each other within a band of 1.5 °C during winter. Additional plots have been produced for other combinations of walls and points can be found in the supplied dataset [58].

Figure 7 Measured Θ during second winter period. Measurements from Wall 2, 3, 5 & 6 in Point 5: Wall plate. Additional plots have been produced for other combinations of walls and points can be found in the supplied dataset [58].

The average temperatures in the summer period from May until October do in general show similar values for all measurement points. Studying the measured boundary conditions in Figure 5, it can be seen that the difference in temperature between indoor and outdoor climate is low, explaining the similar measurements at wall points.

The order of temperature conditions in the points/walls change during the winter periods. A zoom on the winter period to emphasize the changes has been illustrated for the wall plate in Figure 7 with similar zooms for other measurement points and walls in [58]. Taking the temperatures in the un-insulated wall as reference, the changes presented in Table 3 are observed when installing thermal insulation.

	Point 3 & 4: Interior surface	Point 3: Original masonry surface	Point 5: Wall plate	Point 6: Wooden beam end
Wall 5: Reference wall	Reach running average surface temperatures down to 13 °C.			
Wall 2: Insulated	Reach a minimum of 17 °C.	The average temperature of the original masonry surface behind the insulation decreases by up to 10 °C	The average temperature in the wall plate is decreased by 2- 5 °C.	The average temperature in the wooden beam end is decreased by 1- 4 °C.
Wall 3: Insulated & hydrophobized	The surface temperature of the deliberate thermal bridge is in the range			
Wall 6: Insulated, hydrophobized & deliberate thermal bridge	between insulated and un-insulated, with a minimum of 15 °C		Partly replacing thermal insulation with a thermal bridge change the decrease to 2-4 °C.	Partly replacing thermal insulation with a thermal bridge change the decrease to 1-3 °C.

Table 3 Temperatures in measurement points of presented walls during winter periods, compared to reference wall. Investigated based on figures in supplied dataset [58] and Figure 7.

The measurements from the digital RH/T sensors have been validated by simple steady state calculations at two time steps, similar to the procedure used in [17]. The calculations have been based on the thermal material properties listed in Section 2.1.3, with an in- and outdoor convective heat transfer coefficient of $0.13 \frac{m^2K}{W}$ and $0.04 \frac{m^2K}{W}$ respectively. The measured and calculated temperatures for measurement points in the reference Wall 5 can be seen in Table 4, while similar measured and calculated values for the insulated Wall 2 can be seen in Table 5. Comparing the simplified steady state calculations based on λ_{dry} to the measurements in the transient field study, it is concluded that the measurements from the field study are validated and follow theory.

Time		Outside amb. air	Point 1	Point 2	Point 3	Point 4	Inside amb. air
2016.10.10 12:00	Meas.	9.3 °C	11.6 °C	13.4 °C	16.5 °C	-	19.7 °C
	Calc.	-	10.8 °C	13.3 °C	16.7 °C	-	-
	Dif.	-	-0.8 °C	-0.1 °C	+0.2 °C	-	-
2017.02.01 12:00	Meas.	2,6 °C	6.1 °C	9.6 °C	15.0 °C	-	20.1 °C
	Calc.	-	5.2 °C	9.3 °C	15.0 °C	-	-
	Dif.	-	-0.9 °C	-0.3 °C	0 °C	-	-

Table 4 Comparison between simplified steady state calculations of temperature and temperature measurements from transient field study in wall sensor points. Reference Wall 5.

Time		Outside amb. air	Point 1	Point 2	Point 3	Point 4	Inside amb. air
2016.10.10 12:00	Meas.	9.3 °C	10.5 °C	10.7 °C	11.7 °C	18.2 °C	19.7 °C
	Calc.	-	9.7 °C	10.3 °C	11.1 °C	19.1 °C	-
	Dif.	-	-0.8 °C	-0.4 °C	-0.6 °C	+0.9 °C	-
2017.02.01 12:00	Meas.	2,6 °C	4.1 °C	5.1 °C	6.9 °C	17.4 °C	20.1 °C
	Calc.	-	3.2 °C	4.2 °C	5.6 °C	19.2 °C	-
	Dif.	-	-0.9 °C	-0.9 °C	-1.3 °C	+1.8 °C	-

Table 5 Comparison between simplified steady state calculations of temperature and temperature measurements from transient field study in wall sensor points. Insulated Wall 2.

3.3.2 Relative humidity from digital RH/T sensors and calculated mould index on interior surface

Measured relative humidity and calculated mould index in the point closest to the interior surface can be seen in Figure 8. The sensor point differs for insulated and reference walls, being Point 3 for reference Wall 5, Point 4 for insulated Walls 2, 3 and 6 and Point 10 for Wall 6 (the deliberate AAC thermal bridge).

Figure 8 Measured RH and calculated M throughout monitoring period. Sensor points at interior surface: Point 3 for reference wall 5, Point 4 for insulated walls 2, 3 and 6 and Point 10 for Wall 6 with deliberate thermal bridge. Measurements within stabilization period are influenced by initial conditions.

No risk of calculated mould growth is observed at the interior surfaces. The relative humidity on the interior surface of the walls are influenced by the following factors: The moisture content and material properties of the surface material, the surface temperature and the humidity of the indoor air. All walls are influenced by similar humidity from the indoor climate, while the surface temperature and material differ for the masonry surface of the reference wall (sensor Point 3 of Wall 5), the interior insulation surface (Point 4 of Walls 2, 3 and 6) and the interior surface of the deliberate thermal bridge (sensor Point 10 of Wall 6). The relative humidity on the interior surfaces (Figure 8) follow the indoor conditions (Figure 5) with an excess to the surface relative humidity caused by the surface temperature and moisture content of the different wall configurations.

The effect of exterior façade impregnation and interior thermal insulation can be observed in Figure 8. During the summer period, the highest surface relative humidity is observed at the surface of the un-hydrophobized walls: The reference Wall 5 and the insulated Wall 2. The surface of the insulation and thermal bridge of the insulated and hydrophobized Walls 3 and 6 show relative humidity which are 5-10 % RH lower than the surface of the reference wall. The measured relative humidity at the surface of the insulated and un-hydrophobized Wall 2 is

between those of the reference and the hydrophobized walls, peaking at values similar to that of the reference wall.

During the winter period, the highest surface running average relative humidity is observed on the un-insulated interior surfaces: The masonry surface of Wall 5 (84 % RH) and the surface of the deliberate thermal bridge of Wall 6 (82 % RH). The surface of the insulation on Walls 2, 3 and 6 show running average relative humidity values 10-15 % RH lower than those of the reference wall.

3.3.3 Relative humidity from digital RH/T sensors and calculated mould index on interior masonry surface, behind insulation

Measured relative humidity and calculated mould index in Point 3, masonry/insulation interface, can be seen in Figure 9.

Figure 9 Measured RH and calculated M throughout monitoring period. Sensor point in interior masonry surface, Point 3, in insulated walls 2, 3 and 6. Measurements within stabilization period are influenced by initial conditions.

The heat flow to the masonry wall is reduced by applying thermal insulation to the interior surface. The combination of reduced heat flow and diffusion open insulation, allowing diffusion of moisture from the indoor climate, can cause condensation to form on the interior masonry surface.

This effect can be seen in Figure 9 with condensation during the winter in Point 3 for all insulated Walls 2, 3 and 6. The diffusion open system is designed to allow drying to the interior side, but the un-hydrophobized Wall 2 never drops below a running average of 85 % RH. Reduction of rain intrusion by hydrophobation gives a positive effect during summer in Wall 3 and 6, resulting in a minimum of the running average of 70 % RH. The calculated mould indexes for the insulated walls show worsened conditions, resulting in a calculated mould index of $M = 2.9$ for Wall 2 and expected similar results of $M = 1.0$ and $M = 1.3$ for Wall 3 and 6.

The results are obtained after 1 year of mould index calculation, with a rising tendency in the winter period. Mould index exceeding 3 in interfaces is unacceptable as defined by Viitanen et al. [44], which is expected when analysing longer datasets.

The measured relative humidity is in accordance with results of previous research describing that the hydrophobation has a positive effect for the application of interior insulation [24]. The effect is however not sufficient to ensure that moisture induced damage do not occur with the boundary conditions applied in the field study.

3.3.4 Relative humidity from digital RH/T sensors and calculated wooden decay mass loss in wall plate

Measured relative humidity, calculated activation process and wooden decay mass loss in Point 5, the wall plate, can be seen in Figure 10. Comparison between digital and electrical resistance based measured values in the wall plate have been done later in this section.

Figure 10 Measured digital RH, calculated α and ML from digital measurements throughout monitoring period. Sensor point in wall plate, Point 5, in reference and insulated walls. Measurements within stabilization period are influenced by initial conditions.

The running average relative humidity in the wall plate in Figure 10 is analysed based on observations from the increasing components in the wall compositions.

1. Reference Wall 5 shows high RH in winter, decreasing during summer. Calculation of wooden decay shows risk of damage in the period May until July.
2. Applying interior insulation in Wall 2 increases the RH as the temperature decreases. This effect is clearest during winter when the temperature difference is the largest, as seen in Figure 7. Calculation of wooden decay shows risk of damage in the period April until July.

3. Hydrophobation of the exterior surface in Wall 3 reduces the RH in the wall plate during the summer period to a lower level than reference Wall 5. A rapid increase is seen in the winter period, peaking close to the level of both of the un-hydrophobized Walls 2 and 5. Calculation of wooden decay shows that hydrophobation reduces the risk, with no calculated damage.
4. Inserting a deliberate thermal bridge next to the wall plate in Wall 6 increases the temperature during the winter period in the wall plate, compared to the insulated cases in Wall 2 and 3 resulting in reduced RH. Calculation of wooden decay shows that the deliberate thermal bridge further reduce the risk, with no calculated damage.

The damage observed in the reference Wall 5 emphasise the need to control the indoor humidity load in buildings, for instance by installing mechanical ventilation.

Correlation between measurements in the wall plate in Figure 10 and in the masonry wall in Figure 13 is observed. Based on this observation, it can be concluded that the moisture content in the masonry wall influences the conditions in the wall plate.

The measured RH from the digital sensors have been compared against the resulting calculated RH from manual electrical resistance measurements in the wall plate in Figure 10. Similar results were observed from the resistance-based measurements, including the shift of highest relative humidity between Wall 2 and 5.

Figure 11 Measured digital RH and RH calculated from electric resistance measurements throughout monitoring period. Sensor point in wall plate, Point 5, in reference and insulated walls.

3.3.5 Relative humidity from digital RH/T sensors and calculated wooden decay mass loss in wooden beam end

Measured relative humidity, calculated activation process and wooden decay mass loss in Point 6, the wooden beam end, can be seen in Figure 12.

Figure 12 Measured RH, calculated α and ML throughout monitoring period. Sensor point in wooden beam end, Point 6, in reference and insulated walls. Measurements within stabilization period are influenced by initial conditions.

No risk of calculated wooden decay is observed in the wooden beam end. We observe that the un-hydrophobized walls: Reference Wall 5 and insulated Wall 2 show similar running average relative humidity in Figure 12, deviating within ± 5 percent over the course of the summer. Hydrophobation of the exterior surface in Wall 3 induced a reduction of the relative humidity during the summer period May 2016 until November 2016, while an increase occurred during the winter period November 2016 until May 2017. The relative humidity in the wooden beam end of an insulated and hydrophobized wall could generally be reduced by increasing the temperature via insertion of a deliberate thermal bridge in Wall 6, thus reducing the increase during the winter period to that of the un-hydrophobized Walls 2 & 5. The effect of the hydrophobation is further discussed in Section 3.3.7.

Correlation between the measurements in the wooden beam end in Figure 12 and the masonry wall in Figure 13 is observed. Based on this observation, it can be concluded that the conditions in the wooden beam end follow the moisture content in the masonry wall influence.

3.3.6 Relative humidity from digital RH/T sensors mounted in brick near exterior masonry surface and in middle of masonry wall

Measured relative humidity and temperature in bricks in Points 1 and 2, Wall 2 and 3, can be seen in Figure 13.

Figure 13 Measured RH and Θ throughout monitoring period. Sensor points in masonry wall: Point 1 & 2. Un-hydrophobized and hydrophobized insulated Wall 2 & 3. Measurements within stabilization period are influenced by initial conditions.

The temperatures measured in the insulated and un-/hydrophobized Wall 2 and 3 in [58] and Figure 13 show similar temperatures in Point 1, close to the exterior masonry surface, and temperatures approximately 1 °C higher in the hydrophobized Wall 3 in Point 2, the middle of the masonry wall, during the winter period.

The relative humidity measured in the two walls follow the same tendency, with higher values observed in the un-hydrophobized Wall 2, averaging at 90% RH during summer and saturation (100 % RH) during winter. The similar measurements from the hydrophobized Wall 3 show averaging at 70 % RH during summer, peaking at 90 % RH during winter. Relative humidity measured in the middle of the masonry wall indicate saturation in the un-hydrophobized Wall 2 in Figure 13, while the hydrophobized Wall 3 show measurements following the exterior side during summer and saturation during winter.

3.3.7 Summing up on exterior hydrophobation

The application of interior diffusion open insulation pose a risk of condensation on the interior surface of the masonry, as can be seen in Figure 9. As hydrophobation reduce the rate of drying of water through the hydrophobized depth at the exterior surfaces [35], this potential condensate water will have reduced possibility to evaporate to the cold and dry outdoor Danish winter climate. The result of the hydrophobic façade treatment can be seen in the rapidly inclining RH in winter period for hydrophobized walls. This effect was especially seen on the wooden beam end in Figure 12, discussed in Section 3.3.5.

3.4 Influence of rain deposited on building façade

A study on the influence of wind driven rain deposited on the building façade has been performed based on plotting non-smoothened point measurements against wind driven rain and running average indoor and outdoor relative humidity. The following two stabilized periods have been emphasized: 2nd summer period in Figure 14, and 2nd winter period in Figure 15. The measurements include the wall plate and the wooden beam end, Point 5 and Point 6 respectively, from the insulated and un-hydrophobized Wall 2 and hydrophobized Wall 3.

A large rain event can be seen in Figure 14, in the beginning of July 2016, depositing an average r_{vb} of 7.3 l/m² over 10 days from the 1 calculated and 2 measured WDR amounts. The rain event results in a short-term increase in relative humidity 9 days after the end of the rain event. A similar, but smaller increase can be seen from the less intense but longer rain event in August 2016. Based on this result, it is concluded that large rain events during the summer period only lead to temporary increases in relative humidity in wooden elements with a time gap between the event and the reaction. The relative humidity measurements in the hydrophobized Wall 3 declines at a faster rate in the summer than the un-hydrophobized Wall 2, while the rain events have a larger temporary influence on the relative humidity recorded in the hydrophobized wall.

Figure 14 Non-smoothened measurement in walls during 2nd summer period together with in- and outdoor RH and WDR. Measurements from wooden elements, Point 5 & 6, in insulated Walls 2 & 3.

During the winter period in Figure 15, the rain events do not result in similar temporary increases in relative humidity. A more general increase induced from the winter period is seen throughout the period. The hydrophobation issue for cold climate discussed in Section 3.3.7 results in the increase in relative humidity for the wooden beam end of the hydrophobized Wall 3, exceeding values of the un-hydrophobized Wall 2 as the hydrophobation decreases the liquid transport and thereby drying potential to the outdoor cold and dry air.

Figure 15 Non-smoothed measurement in walls during 2nd winter period together with in- and outdoor RH and WDR. Measurements from wooden elements, Point 5 & 6, in insulated Walls 2 & 3.

4 Conclusion

The paper presents the first results from a large field study, investigating the effect of applying thermal insulation to the interior side of characteristic historic solid masonry walls. The study includes combining measures to cope with the changed moisture conditions when applying interior thermal insulation. One being application of a hydrophobizing agent to the exterior masonry surface, another being the implementation of a material/thermal bridge with a higher thermal conductivity next to the wall plate and wooden beam, to increase the heat flow to the wooden elements.

The investigated thermal insulation consisted of 100 mm lightweight AAC, installed strictly following the producer's description, to a 360mm thick solid masonry wall. The exterior surface was exposed to a Danish climate, with an indoor climate of 20 °C and 60% RH. Continuous digital RH/T measurements were performed at multiple positions throughout the masonry wall, in the insulation and in the wooden elements.

The hydrophobizing agent has a varying effect on the measured conditions in the walls depending on season, where the hydrophobation limits the transport of moisture towards the exterior surface during winter, and thereby the evaporation to the cold and dry Danish climate. In the summer, when moisture transport is towards the interior side, the hydrophobation reduces the measured RH in the measurement points.

Damage models were implemented to evaluate the different hygrothermal responses when installing thermal insulation to the interior masonry surface in different variations. Even though the models cannot be expected able to precisely predict evolution of damage, they still show a reference value higher or lower than the initial conditions in the reference wall. Measurements at the masonry surface, behind the interior insulation, showed that the hygrothermal conditions were worsened as the investigated thermal insulation product would not be able to

keep the RH below critical levels during the winter period, resulting in unacceptable calculated mould index > 3. Based on the found mould indexes behind the thermal insulation material in Section 3.3.3, compared to no calculated mould germination/growth on the un-insulated wall in Section 3.3.2, only the un-insulated wall indicate a viable construction.

Measurements in the wall plates showed a calculated risk of wooden decay for the reference and insulated wall, but also showed that hydrophobation and implementation of a deliberate thermal bridge could improve the hygrothermal conditions in the construction.

The deliberate thermal bridge is shown to reduce the RH in the wooden elements, reducing the increase in RH from hydrophobation during winter to that of the reference and insulated wall in the wooden beam end and to a maximum level under 80 % RH for the wall plate.

Investigation of wind-driven rain showed that even though hydrophobation overall reduced the RH in measurement points, it was not possible to see an effect after large rain events in the wooden elements.

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The data logging systems have been bought from the following respective companies: The vertical rain gauges are "RG3-M HOBO Rain Gauge" from "ONSET". The digital RH/T sensor module are "HYT 221" from "Innovative Sensor Technology IST AG". The connection from the sensor module was established with "sensorcable for EK-H3/H4" from "Sensirion AG".

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