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Retrofit with Interior Insulation on Solid Masonry Walls in Cool Temperate Climates – An Evaluation of the influence of Interior Insulation Materials on Moisture Condition in the Building Envelope

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Abstract

For historic buildings, where an alteration of the exterior façade is not wanted, interior insulation can be the solution to improve the indoor climate and reduce heat loss, but might also introduce moisture problems like condensation in the wall. Capillary active/hydrophilic insulation materials have been introduced to cope with the moisture problem. An extensive amount of calculations indicating where the challenges lie in the complex work with interior insulation in cool temperate climate has been carried out. In areas with high precipitation like Denmark, capillary active insulation may not be feasible without additional driving rain protecting of the façade.

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1. Introduction

To meet the world's strive to reduce fossil fuels as an energy source in buildings, one of the methods is to apply building insulation. Insulation of new buildings are already included by legislation in Denmark, but new buildings only represent a minor percentage of the existing Danish building stock. The existing building stock has been seen to represent a huge potential in energy savings, based on the size of the segment and the individual potential.

The best solution from a building physical point of view is to insulate the exterior side of existing buildings [1, 2, 3]. Exterior insulation is, however, not suitable from different reasons, e.g. from the point of view of the protection of the cultural heritage. For a considerable part of the segment, it may be accepted that they are insulated at the interior side, to enable the occupants to obtain an indoor climate and comfort that meet modern requirements. A typical example is worth preserving buildings, where preservation of original architectural features of the exterior facade is mandatory [4].

However, interior insulation systems have two disadvantages, which must be accepted, 1) that thermal bridges are not completely eliminated, and 2) that there is a reduction of the indoor space. Of challenges to be adressed, the following three can be mentioned: 1) the risk of frost damage in the exterior wall, caused by the decrease in the wall's temperature when interior

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insulating materials are applied. 2) The system must be able to cope with the moisture/quantity of water that penetrates from the outside due to wind-driven-rain. 3) The risk that the warm moisture-containing air from the interior will penetrate to the outer wall and condense [4].

A standard solution for interior insulation in Denmark is to apply mineral wool insulation between rafters mounted to the existing wall with a vapor barrier, e.g. polyethylene film, between the inner plasterboard and the insulation layer, so that both the insulation layer and the existing outer wall is protected from water vapor from inside. A risk exist that sufficient tightness of the film is not ensured or that it subsequent will be mechanically damaged. This means that there may be harmful vapor condensation in the insulation system [5]. Another risk with this solution is that ingress of water/moisture from the outside will accumulate in the structure behind the vapor barrier.

Mold occurs in many cases due to condensate on the colder existing wall. Many existing solid masonry walls have embedded wood [6], e.g. the beam ends of the wooden floor structure. When the temperature at the beam end is lowered caused by the interior insulation, there is a risk of mold growth and rot damages [7, 8]. This can be countered in various ways, e.g. by not insulating around the beam end [7, 8], or by other ways raising the temperature around the beam end [9, 10]. For interior insulation, thermal bridges occur where a transverse wall meets an outside wall. The use of vapor barrier is problematic because it is very difficult to apply correctly to ensure vapor tightness, especially in the later period of use.

There are several examples of insulation systems where a vapor barrier either is omitted or replaced by a layer that reduces moisture transport without preventing it [3, 4, 5, 11, 12, 13, 14]. There are a number of studies that test hydrophilic materials [3, 11, 14, 15, 16, 17] with good results. However, there is a need to test some of these materials' usability as interior insulation in a cool temperate climate, seen in a holistic context involving the influence of driving rain, moisture from inside, the wood embedded in the wall and the robustness and suitability for interior wall material in a dwelling.

Projects with calcium silicate to solve some of these problems have been carried out [5, 18], but calcium silicate plates have a higher thermal conductivity (0.057 W/mK) than similar mineral wool insulation (0.04 W/mK). Consequently, other materials with a lower thermal conductivity such as e.g. Autoclaved aerated concrete (AAC) (0.04 W/mK) and a capillary active thermal insulation system based on rigid PUR-foam panels (0.033 W/mK) are equally interesting to test in order to find a suitable solution for interior insulation.

No matter which insulation material is used, application of interior insulation will change the hygrothermal behavior of the wall, leading to higher average moisture level, since the dry-out effect of the wall is hampered by the insulation. Thus, when adding interior insulation, potential moisture problems are introduced to historical buildings that have been functioning well for centuries. While exterior insulation systems protect the external wall against rain, this effect is lacking in interior insulation. Thus, it is not only the interstitial condensation that worsens the internally insulated façade's moisture balance, but also the driving rain load, since a relatively high amount of rainwater (up to 70 %) is absorbed through capillary suction. The more porous a material is, the more water the wall can contain. Historic unplastered masonry brick façades that are made of porous brick are therefore especially exposed.

Façade impregnation/paint with water repellent effect, e.g. siloxanes, has been shown to improve the moisture behavior of exposed masonry walls when interior insulation is applied [12]. Although these impregnations have been used to protect structures against moisture, biological growth and chlorides for several decades, an improvement of the functionality of interior insulation was only seldom the purpose. The impregnation can penetrate ~ 20-50 mm deep into the pores and block the liquid water transport, but allowing the water vapor and CO_2 to get through. Nevertheless, there is a delay of the dry-out process [19]. Since the thermal conductivity of the wall is depending on its moisture content [20], impregnations can improve the thermal envelope's functionality substantially.

2. Method

Several models using three different capillary active/hydrophilic insulating materials including Autoclaved Aerated Concrete (AAC), calcium silicate board and a capillary active thermal insulation system based on rigid PUR-foam panels, IQ-Therm, have been tested in hygrothermal one-dimensional numerical simulations in the simulation software WUFI (http://www.wufi.de). In WUFI, it is also possible to simulate cracks/damaged mortar joints, by defining an area with negative source strength and a certain depth. The materials have been tested based on a case concerning a parapet on the first floor of the historic Borch's dormitory in Copenhagen from 1825. The change in heat and moisture movement through the external wall has been monitored with changes in insulation thicknesses (30 – 100 mm) and with/without driving-rain protection through impregnation ($S_d = 0.1$ m). The parapet wall is a 228 mm thick, uninsulated solid brick wall, plastered with lime mortar on the interior side (S_i) and not plastered on the exterior side (S_e). The explicit data for the mortar and brick in this wall was not available; instead the data in WUFI for historical buildings were used. Insulations are affixed on the original wall with product-specific adhesive providing full contact between the wall and insulation necessary for the capillary active insulations to work.

The analysis was done stepwise; in step 1 the moisture behavior and risk of mold growth behind the insulation and on the interior surface are investigated. Due to a high number of models, only the ones that have shown acceptable, moisture-safe results in step 1 have been included and further analyzed in step 2 regarding the heat loss and minimum temperatures on the interior and exterior surface. Table 1 shows the wall assemblies for the analyzed models.

Table 1. Models and wall assemblies

Model	Damaged mortar joint	Impregnation(S_d= 0.1 m)	Original wall (historic brick)	Adhesive for insulation	Insulation type	Insulation thickness	U-value [W/m²K]
A 1	-	-	✓	-	-	-	1.770
A 2	-	✓	✓	-	-	-	1.769
D 1	-	✓	✓	Calsitherm adhesive mortar	Calcium silicate	30 mm	0.870
D 2	-	✓	✓	Calsitherm adhesive mortar	Calcium silicate	50 mm	0.674
F 2	-	✓	✓	IQ-fix	IQ-Therm	50 mm	0.458
X 2 (D1')	✓	✓	✓	Calsitherm adhesive mortar	Calcium silicate	30 mm	0.870
X 3 (F2')	✓	✓	✓	IQ-fix	IQ-Therm	50 mm	0.458

The analysis in step 1 was conducted based by the following questions:
- Is the relative humidity between the wall and the insulation > 80 % (within a 10-year period)?
- Is the relative humidity on the interior surface (RH_{Si}) > 80 % (within a 10-year period)?
- Is there risk of mold growth (Mould Index > 1) between the wall and the insulation (within the last year of a 10-year period)?
- Is there risk of mold growth (Mould Index > 1) on the interior surface (S_i) (within the last year of a 10-year period)?
- Which influence on the hygrothermal behavior of the wall has a damaged mortar joint with a depth of 1 cm?

The analysis in step 2 was based on the following questions:
- What is the heat loss (Q) through the interior surface (S_i)?
- How much is the heat loss (Q) through the interior surface (S_i) of the impregnated/insulated wall compared to the unimpregnated/uninsulated wall (heat loss reduction)?
- What are the maximum RH and minimum temperatures at the exterior ($T_{Se, min}$) and interior ($T_{Si, min}$) surfaces during the last year of a 10-year period?

Step 2 was carried out as a time-of-wetness (TOW) analysis, as introduced by Adan [21] being a measure "for the water availability for fungal growth under transient conditions". Simply by measuring how long (percent of time) the exterior and interior surfaces are wet at a certain critical temperature, it can be evaluated to which extent the wall is exposed to several moisture-related risks (mold growth, condensation and frost). There is risk of mold growth, when the relative humidity is above 80 % and the temperature is over 0° C. When the relative humidity is above 95 %, there is also risk of decay, condensation and growth of algae of the structure. There is risk of frost, when the relative humidity comes above 95 % and the temperature drops under 0° C [22].

WUFI input data for boundary conditions in the hygrothermal calculations have been chosen as real as possible (inclination of the building: 90°, color of façade surface: bright, interior climate: normal load) except for some factors that have been over-dimensioned for safety reasons. This applies to the direction of the façade, where the SW direction that is most exposed to driving rain was investigated instead of NW direction. Furthermore, the building height has been chosen as tall building (> 20 m) although it in reality is less than 10 m as higher buildings are more exposed than lower buildings to wind-driven rain. Weather data were not available for Copenhagen in WUFI, so Lund/Sweden (40 km East of Copenhagen) climate was used instead. The two cities have comparable continental climate with warm summers and with significant precipitation in all seasons, since they both belong to the same climate type (Köppen-Geiger climate classification Dfb). The driving rainwater absorption (adhering fraction of rain) was set to 70 % (default by WUFI) in original case and 1% in models with façade impregnation.

3. Results

The results of step 1 for all wall assemblies (with different AAC, CS and IQ-Therm insulation thicknesses, with and without driving rain protection) in terms of RH and Mold Index behind insulation and on the interior surface for the last year of a 10-year period and necessary details of the construction and material properties have been described in [23]. The study showed that in case of all insulation types in all thicknesses, too much moisture accumulated behind the insulation (RH > 80 %) with subsequent unacceptable high risk of mold growth (Mould Index 6, where the max. tolerable value is 1). Application of insulation resulted nevertheless in a dry interior surface vs. wet surface in the original wall with one exception, since the two calcium silicate insulations (30 and 60 mm thick) showed high relative humidity even in the over hygroscopic range and thus mold risk on the interior surface (room side). In all cases, the use of additional façade impregnation resulted in a dryer surface behind the insulation and at the surfaces of the interior side of the insulation without risk of mold growth.

Table 2. TOW analysis (Last year of 10-year period).

Parameters	Model A 1	Model A 2	Model D 1	Model D 2	Model F 2	Model X 2	Model X 3
$T_{Si, min}$: [^{o}C]	9.2	14.5	17.4	18.0	18.7	17.4	18.5
RH $_{Si, max}$: [%]	100	66	63	62	62	63	62
Heat Loss $_{Si}$ (Q): [W/m^2]	35.3	19.4	9.65	7.51	5.13	9.74	5.16
Heat loss reduction: [%]	Ref.	45.04	72.66	78.73	85.47	72.41	85.38
TOW (frost)							
TOW $_{Frost\_Se}$: [% of time]	0.67	0	0	0.01	0	0	0
TOW $_{Frost\_Si}$: [% of time]	0	0	0	0	0	0	0
TOW (mold, corrosion)							
TOW $_{Mold\_Se}$: [% of time]	54.39	29.03	41.84	44.29	46.64	42.68	47.35
TOW $_{Mold\_Si}$: [% of time]	21.99	0	0	0	0	0	0
TOW (condensation, algae, decay)							
TOW $_{Condensation\_Se}$: [% of time]	33.50	2.28	5.46	6.58	8.00	5.72	8.26
TOW $_{Condensation\_Si}$: [% of time]	16.84	0	0	0	0	0	0

While impregnation in most cases is a feasible solution, it is not the case of AAC insulation (60, 80, 100 mm), where much moisture still accumulates behind the insulation, most in the thickest (100 mm) and least in the thinnest (60 mm) AAC insulation [23]. Since AAC insulations did not result in a moisture safe solution with façade impregnation, they were omitted in the further TOW analysis presented in the present study.

Table 2 shows the results of some key parameters included in the TOW analysis based on minimum temperature and maximum RH on both the exterior and the interior surface of the façade during the last year of a 10-year period. In addition, the heat loss through the interior surface is given in total numbers and as the heat loss reduction compared to the original, uninsulated and unimpregnated historic brick wall. Fig. 1 shows the graphical presentation of the results above, where it can be seen how the interior surface temperature increases after impregnation and additional insulation, how the moisture load on the interior surface decreases from 100 % to an acceptable level under 80 % and how the heat losses decrease when the façade is impregnated and even further when it is insulated.
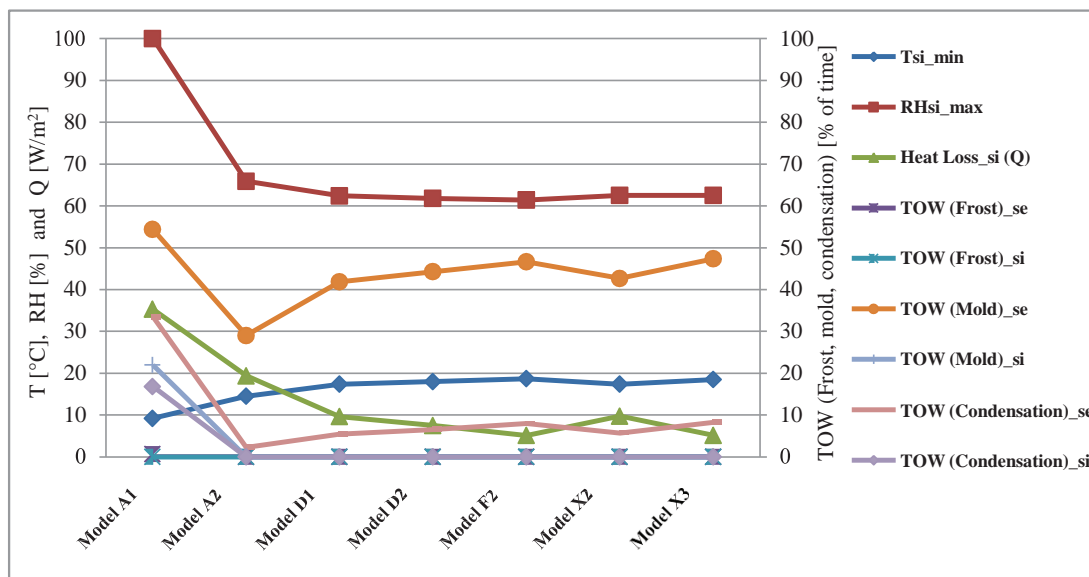

Fig. 1. Graphical presentation of TOW analysis (Last year of 10-year period).

4. Discussion

In the design phase of a retrofit project, the possible models with different insulation types and thicknesses can be evaluated by looking at which model performs best meaning that the time of wetness must be as low as possible, the temperature on the interior surface must be as high as possible, the heat loss through the interior surface must be minimised and the U-values must be as low as possible.

In the present study, only insulations were included that fulfilled the requirement of no moisture risk behind the insulation, which excluded AAC insulation. Thus, only calcium silicate board and IQ-Therm insulation with a façade impregnation were included, since models without façade impregnation also had high moisture risk behind the insulation.

Adding thermal insulation made the living room warmer as a result of major gains in minimum temperature at the interior surface due to an increase from around 9.2° C (uninsulated wall) to around 18.7° C in the model with the best thermal insulation (Model F2 incl. 50 mm IQ-Therm insulation). The maximum relative humidity on the interior surface decreased in all models from 100 % (uninsulated wall) to a value much under the critical 80 % limit with only little variation. Thus, the model with the best thermal insulation (Model F2) also had the lowest RH_{max} (62 %).

Thermal insulation resulted in a significant decrease of heat losses through the interior surface (range 45–85.5 %). They correspond to the minimum temperatures, since the model with the lowest heat loss is the model with the warmest surface. When comparing 50 mm CS board and IQ-Therm insulation respectively, IQ-Therm had ~ 6 % less heat loss than CS and thus a higher surface temperature (0.7° C), but with the same moisture load. It can therefore be concluded that only minor differences exist between the performance of these 2 insulations.

The TOW analysis for frost risk revealed that on both the exterior and interior surface, it is close to zero, since it only occurs on the exterior surface in 0.01 % of time corresponding to 1 single hour in Model D2 during the last year of a 10-year period. However, this is a reduction from 0.67 % of time corresponding to 59 hours that were apparent in Model A1 (the uninsulated wall). Thus, TOW_{Frost} is no problem in the suggested models.

The TOW analysis for risk of mold and corrosion on the exterior surface shows another picture, since this is the only surface that is wet for a significant time due to driving rain. While the $TOW_{Mold, corrosion}$ in the original wall was apparent in 54 % of time, it dropped to 29 % of time in Model A2 with impregnation. Increasing values are seen for the models with insulation (max. 47 %). Thus, adding façade impregnation improves the situation somewhat, while adding interior insulation worsens it. Nevertheless, the risk of mold growth is negligible due to the fact that UV-radiation inhibits mold growth, but corrosion can occur on ungalvanised metallic parts on the exterior surface. However, on the interior surface there is no risk of mold and corrosion, which is an improvement, compared to the original wall, where there was risk of mold growth during 22 % of time.

The risk of condensation, algae growth and general decay on the exterior surface is very low in the proposed models, since $TOW_{Condensation}$ only occurs in 2 % of time in the model with the shortest wetness exposure (Model A2) and 8 % of time in the model with the longest wetness exposure (Model X3). That is very different from the 33 % of time during which the original wall (Model A1) is exposed. There is no risk of condensation on the interior surface in the proposed models, which is also an improvement compared to the original wall, where this was apparent during 17 % of time.

The model without insulation but with impregnation (Model A2) also showed a significant increase in minimum temperature at the interior surface (+ 5.3° C) while achieving a low RH_{max} (66 %) and around 45 % lower heat loss than the original wall. Even if the reduction should be smaller due to the limitations of the one-dimensional model, it still shows a remarkable figure. The impregnation adds to the U-value of the wall system due to the fact that a dry wall insulates much better than a wet wall. Consequently, this model has the driest façade of all suggested models with the least exposure to moisture-related risks due to the very limited wind-driven rain load and lack of insulation that lowers the risk of condensation as a consequence of a temperature drop behind the insulation, helped by lower wall thickness that enables quicker dry-out.

The effect of a damaged mortar joint with a depth of 1 cm on an impregnated façade was shown to be locally limited behind the façade, since it had only a neglectable effect on the area behind the insulation or interior surface. The point of concern is, however, that a lot of moisture can penetrate the wall through such damaged mortar joints resulting in a wetter wall around and behind the damaged mortar joint, with the risk of resulting frost damage of the façade and subsequent higher heat loss due to a wetter wall. Although the evaporation of the moisture is impaired because of the impregnation [24], this is not the main reason for the wetter wall. The main reason is rather a lot of run-off from the impregnated façade into the damaged mortar joint and thereby creating a higher moisture load on the crack in the impregnated façade than it would do in an unimpregnated façade [25]. Due to aging, historical buildings are often characterized by cracks and damaged mortar joints leading to water ingress and higher moisture content and freezing risks behind the façade. To avoid these problems, repair of such damages is mandatory before the façade can be impregnated. In the present study, only one single damaged mortar joint was included in the simulations and that did not change the results significantly. However, if many damaged mortar joints exist that are not repaired, the outcome will be less favorable.

5. Conclusion

The study conclude that an existing building with/without interior insulation and a well-kept diffusion-open impregnated masonry façade will perform better than a masonry façade without this water-repellent treatment, from a hygrothermal and heat flux point of view. Capillary active insulation materials as well as façade treatments have obviously advantages and disadvantages, but more research is needed to identify the cases where the use of interior insulation results in moisture-safe solutions and where other solutions must be chosen.

In areas with high precipitation like Denmark, the use of capillary active insulation applied to exposed masonry walls may not be a suitable solution, unless a driving rain protection is added to the façade due to moisture accumulation behind the insulation, at least when the wall is relatively thin. Siloxane-based façade impregnations on un-protected masonry walls may be chosen when a structural driving rain protection is not possible, for example by roof overhangs.

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