Influence of envelope properties on interior insulation solutions for masonry walls

Xiaohai Zhou^{1,2}, Jan Carmeliet^{1,2} and Dominique Derome²

¹Chair of Building Physics, ETH Zürich, Zürich, Switzerland

²Laboratory of Multiscale Studies in Building Physics, Empa, Dübendorf, Switzerland

Corresponding author: Xiaohai.zhou@empa.ch

Abstract

Energy efficiency in historical buildings with a worth-preserving appearance can be improved with interior thermal insulation. However, interior thermal insulation may change significantly the hygrothermal performance of the building envelope and increases the risk of moisture problems in the assembly components. This paper studies the influence of different wall structures, types of exterior render and brick and vapor control strategies on the moisture performance of internally insulated walls with vapor-open insulation for different climatic conditions in Switzerland. The hygrothermal performance is simulated with a coupled heat and mass transport model and evaluated using a hygrothermal indicator, called the RHT Index. The numerical analysis indicates that the hygrothermal performance of interior insulated walls depends mainly on the moisture performance of the exterior finishing render. A capillary active render with larger liquid permeability leads to higher moisture contents in the building envelope. The influence of parameters such as masonry structure and brick type on envelope hygrothermal performance is rather small. For wall envelopes with less capillary active renders, the need to use a vapor barrier depends on the risk for water leakage and the vapor resistance of the render.

Keywords: interior insulation energy retrofit; vapor-open thermal insulation; massive masonry wall; hygrothermal modelling; different climatic conditions

This document is the accepted manuscript version of the following article:
Zhou, X., Carmeliet, J., & Derome, D. (2018). Influence of envelope properties on interior insulation solutions for masonry walls. *Building and Environment*, 135, 246-256.
<http://doi.org/10.1016/j.buildenv.2018.02.047>
This manuscript version is made available under the CC-BY-NC-ND 4.0 license
<http://creativecommons.org/licenses/by-nc-nd/4.0/>

1. Introduction

Given that buildings account for over one third of the global total final energy consumption in the world, it has been long identified that the existing building stock with its low energy efficiency has a significant potential to reduce energy consumption [1]. The energy efficiency of the envelope of existing buildings can be improved by retrofit measures, such as adding interior or exterior thermal insulation. For historical buildings with a worth-preserving appearance, interior wall insulation is the only available solution to improve building energy efficiency. However, adding interior thermal insulation changes significantly the hygrothermal performance of building envelope assemblies [2, 3]. For massive load-bearing masonry walls, the addition of interior thermal insulation may cause performance and durability problems. For a cold climate, when a masonry wall is insulated from the inside, the interior insulation layer reduces the heat flux from inside into the masonry wall. Consequently, the wall drying ability decreases, leading to lower temperatures and higher moisture levels in the masonry walls, leading to, for example, interstitial condensation and mold growth, freeze-thaw damage of the brickwork or decay in embedded wood structures .

Given the needs for energy efficiency, the complexity of this problem and the wide range of existing building constructions and climates, the hygrothermal performance of a masonry wall retrofitted with interior insulation has retained a lot of attention in the last years [3-14]. Experiments and numerical simulations have demonstrated that a vapor barrier is needed on the warm side of the internal thermal insulation layer to avoid condensation in the inner part of the wall during wintertime [3, 15, 16]. However, considering internally insulated masonry walls, such a vapor-tight wall system may limit the drying out of the masonry wall towards the inside environment resulting in a potential risk on moisture related problems. Such reduction of the inward drying potential of the wall assembly during the warm season is shown in [17]. As a result, this type of vapor-tight wall system may be sensitive to rain pene-

tration through building envelope defects. By contrast, in the absence of a vapor barrier, vapor can diffuse freely between the indoor environment and the wall envelope. In fact, both vapor-tight and vapor-open interior insulation systems have advantages and disadvantages. Consequently, the selection of a vapor-tight or vapor-open interior insulation system should be made taking into account the indoor and outdoor environmental conditions, the material properties of building materials and the wall assembly composition.

Indeed, the hygrothermal performance in wall assemblies is strongly affected by local climatic conditions [13, 18, 19]. The moisture content of a wall in Bergen, Norway, can undergo much higher values than the one of a wall located in Gothenburg, Sweden [19]. More specifically, the hygrothermal conditions of building envelopes are affected by their climatic wetting and drying potentials [20]. In terms of wetting potential, the wind-driven rain load (WDR) is often the largest moisture source imposed on an assembly [21]. The amount of wind-driven rain load on the facade is strongly affected by the orientation of the façade [22]. The drying potential is influenced by air temperature, air humidity, wind speed and net radiation [20]. A specific wall envelope system may have a good hygrothermal performance in one climate but not in another [19].

In certain regions such as Switzerland, load-bearing masonry walls are often finished with an exterior finishing render, regularly made of a cement-based plastering finish layer of 10-20 mm thickness, left bare or painted. Previous studies have demonstrated that the material properties of such exterior render affect the water uptake of external walls during wind-driven rain events [23, 24]. Exterior renders with high water absorption coefficient tend to lead to higher moisture content in the wall [24, 25]. On the other hand, moisture in the wall can dry out through the exterior render by vapor diffusion. Therefore, the vapor diffusion resistance of the exterior render plays a definite role in the drying process of the wall. An exterior render

with low vapor diffusion resistance factor tends to lead to low moisture content in the masonry, and vice versa.

Masonry wall can present a variety of compositions. Brick is the most common component of a masonry wall from the industrial age, and was also widespread before. Material properties of different bricks can vary significantly [26, 27]. For example, the water absorption coefficient for six bricks studied by Kumaran *et al.* (2002) varies from 0.0076 to 0.0322 kg/(m²s^{0.5}). Different types of brick may also have an influence on the hygrothermal performance of a wall envelope.

Recently developed, aerogel-based high insulating materials may present a good option for interior insulation energy retrofitting [28-32]. Such aerogel-based insulations are characterized by a low thermal conductivity and a low vapor diffusion resistance, thus providing the possibility to reduce the insulation layer thickness and thus minimize loss of inner space. Although aerogel-based high insulating material shows very good insulating properties, their impact on the hygrothermal behavior of the wall remains to be evaluated for different climates. For a wall envelope internally insulated and subjected to a cold climate, there is a risk of interstitial condensation and thus a risk of moisture-related problems.

In summary, as masonry wall envelopes that have behaved properly in the past are internally retrofitted, changes in the hygrothermal performance of the wall envelopes may increase considerably their moisture levels. Long-term moisture accumulation and exposure may result in moisture-related problems [10, 23]. The long-term hygrothermal performance of wall envelopes post internal retrofits thus needs to be evaluated at the design stage. Hygrothermal models, simulating the coupled transport of heat and moisture in wall envelopes, can be used to assess the long-term heat and moisture performance of wall assemblies and predict the risk for moisture-related damage problems. Thus, the objective of the work is to study the influence of climatic condition, wall structure, exterior render type, brick type and vapor con-

trol strategy on the hygrothermal performance of a massive masonry wall insulated on the interior side with a vapor-open insulation material, i.e. aerogel insulating plaster. Hygrothermal simulations are performed to predict temperature and moisture content distributions in the different wall envelopes and the hygrothermal performance is evaluated based on the RHT Index [26].

2. Methodology

2.1 Heat and mass balances

The governing equations for moisture and heat transport are the following [20, 33]:

Conservation of moisture:

$$\frac{\partial w}{\partial p_c} \frac{\partial p_c}{\partial t} + \nabla \cdot (g_l + g_v) = 0 \quad (1)$$

with

$$\text{liquid flow: } g_l = -K_l \nabla p_c \quad (2)$$

$$\text{vapor flow: } g_v = -\delta_v \times \frac{p_v}{\rho_l \times R_v \times T} \nabla p_c - \delta_v \times \frac{p_v}{\rho_l \times R_v \times T^2} (\rho_l \times L_v) \nabla T \quad (3)$$

Conservation of heat:

$$(c_0 \times \rho_0 + c_l \times w) \times \frac{\partial T}{\partial t} + \nabla \cdot (c_l \times (T - T_{ref}) \times g_l + (c_v \times (T - T_{ref}) + L_v) \times g_v) = -\nabla \cdot (\lambda(w) \nabla T) \quad (4)$$

where w is the moisture content (kg/m^3), p_c is the capillary pressure (Pa), g_l and g_v are the liquid and vapor flow ($\text{kg/m}^2\text{s}$), K_l is the liquid permeability (s), δ_v is the water vapor permeability (s), p_v is the vapor pressure (Pa), ρ_l is the density of water (kg/m^3), R_v is the gas constant of water (J/kg K), T is the temperature (K), c_0 is the specific heat capacity of solids (J/kg K), c_l is the specific heat capacity of water (J/kg K), c_v is the specific heat capacity of vapor (J/kg K), ρ_0 is the density of solids (kg/m^3), T_{ref} is the reference temperature (273.15 K), L_v is the latent heat of vaporization (J/kg), $\lambda(w)$ is the thermal conductivity (W/mK), depending on moisture content.

The moisture and heat transport equation are solved using the finite element simulation program COMSOL. The time-dependent problem is solved by integration of the partial differential equations in time according to an implicit backwards differentiated formula (BDF) method. Numerical time steps are automatically selected by the COMSOL solver, depending on relative or absolute tolerance for the accuracy of the integration.

The capillary pressure curve of building materials is described using the following equation:

$$w = w_{cap} \sum_{i=1}^N \frac{k_i}{(1 + a_i \times \text{abs}(p_c)^{n_i})^{m_i}} \quad (5)$$

where w_{cap} is the capillary saturation moisture content (kg/m^3); k is the weighting parameter, a , m and n are the fitting parameters, $m=1-1/n$; N is the modal number; i is the counter.

The vapor permeability of building materials is expressed as a function of the moisture content:

$$\delta_v = \frac{26.1 \times 10^{-5}}{R_v T \mu_{dry}} \times \frac{1 - (w / w_{cap})}{(1 - \alpha) \times (1 - (w / w_{cap}))^2 + \alpha} \quad (6)$$

where μ_{dry} is the water vapor resistance factor; α is a weighting parameter.

2.2 Wall structures and components

Two types of wall structures, representing typical Swiss walls, are investigated, both of masonry. The first type of wall structure consists of a 380 mm thick masonry wall (3 wythes of brick), while the second type of structure consists of a 250 mm thick masonry wall (2 wythes of brick) (Figure 1). In addition, both walls consist of a 25 mm thick exterior render, a 15 mm thick original plaster at the inside of the existing wall stripped of any original paint layer, a 60 mm thick aerogel plaster and a 15 mm thick interior plaster. One-dimensional modeling is used to study the hygrothermal behavior of the two types of wall structures. The configuration used in the 1 D simulation is shown between the blue dash-dot lines in Figure 1.

Figure 1. Geometry for the two types of wall structures: (a) 380 mm thick masonry wall; (b) 250 mm thick masonry wall.

Renders used in this study are lime mortar, lime plaster, lime cement plaster and mineral plaster, respectively (Table 1 and Figure 2). The short-wave absorptivity and long-wave absorptivity of the renders are kept constant at 0.7 and 0.93, respectively. The renders have different water absorption coefficients and water vapor resistance factors. For example, the lime mortar shows the largest water absorption coefficient ($A_{cap}=0.153 \text{ kg/m}^2 \text{ s}^{0.5}$), while the mineral plaster the smallest ($A_{cap}=0.0017 \text{ kg/m}^2 \text{ s}^{0.5}$). Lime mortar has the largest liquid permeability, while the mineral plaster has the smallest. However, the mineral plaster shows the

largest vapor resistance factor ($\mu_{\text{dry}}=25$), while lime plaster the smallest vapor resistance factor ($\mu_{\text{dry}}=7$). The properties of renders are taken from the WUFI material database [34, 35].

Table 1. Material properties of the exterior renders

	Density (kg/m ³)	Heat capacity (J/kg/K)	Capillary moisture content (kg/m ³)	Moisture retention parameters				Water vapor resistance factor (μ_{dry})	A_{cap} (kg/m ² s ^{0.5})
				N	k	a	n		
Lime mortar	1785	850	247.6	2	0.8 0.2	3.9e-5 4.0e-6	1.45 3.0	15	0.153
Lime plaster	1600	850	250	2	0.2 0.8	8.0e-6 3.2e-7	1.9 1.8	7	0.05
Lime cement plaster	1900	850	210	3	0.21 0.36 0.43	5e-5 2.6e-5 2.0e-7	1.6 1.2 1.4	19	0.017
Mineral plaster	1900	850	210	3	0.21 0.36 0.43	5e-5 2.6e-5 2.0e-7	1.6 1.2 1.4	25	0.0017

Figure 2. Liquid permeability of exterior renders

Two different types of bricks with very different material properties are used (Hagendoft *et al.* 2004, and Table 2 and Figure 3). The capillary moisture content for the first

brick is 373.5 kg/m^3 , whereas it is 157.0 kg/m^3 for the second brick. The first type of brick shows much larger liquid permeability compared to the second type. The former may more or less represent some old bricks with cracks, which have large liquid permeability. The first type of brick has a water vapor resistance factor of 7.5, while the second a water vapor resistance factor of 30.

As mentioned above, aerogel insulating plaster is selected as the vapor-open interior insulation [28]. The material properties of aerogel plaster are shown in Table 2 and Figure 4. The aerogel plaster has a very small thermal conductivity of 0.028 W/mK and a vapor resistance factor of 4. It consists of lightweight granular silica aerogel and cement free binder. The aerogel plaster is considered suitable for thermally insulating historic buildings and structures with required reversible measures.

The material properties of the mortar are from [36]. The material properties of the original and interior plaster are the same. They are from the HAMFEM material database [33].

Two vapor control strategies are used. The first vapor control strategy is to use a vapor barrier between the interior plaster and the aerogel plaster. The vapor barrier has a vapor resistance factor equivalent to an air layer thickness of 10 m. The second vapor control strategy is without vapor barrier between interior plaster and aerogel plaster.

Table 2 Material properties of brick, mortar, aerogel plaster and interior plaster

	Density (kg/m^3)	Heat capacity (J/kg/K)	Capillary moisture content (kg/m^3)	N	Moisture retention parameters			Water vapor resistance factor
					k	a	n	
Brick 1	1600	1000	373.5	2	0.46 0.54	$4.8\text{e-}5$ $2.0\text{e-}5$	1.5 3.8	7.5
Brick 2	2005	840	157.0	2	0.3 0.7	$1.25\text{e-}5$ $1.8\text{e-}5$	1.65 6.0	30
Mortar 1	230	920	700	2	0.2 0.8	$5.1\text{e-}5$ $4.1\text{e-}7$	1.5 3.8	50
Aerogel plaster	200	1000	400	2	0.8 0.2	$6.9\text{e-}7$ $1.8\text{e-}6$	2.3 2.0	4
Interior plaster	79	790	209	1	1.0	$2\text{e-}6$	1.27	3

Figure 3. Liquid permeability of bricks, aerogel plaster, mortar and interior plaster

2.3 Climatic locations

Switzerland lies in the zone with westerly winds. The prevailing wind transports sea air to Switzerland and are responsible for the precipitation levels in the country. Most of Switzerland enjoys an adequate amount of precipitation throughout the year. Southern Switzerland, which climate is influenced by the Mediterranean sea, is characterized by a much milder climate than northern Switzerland, as the Alps act as a climatic barrier (Meteoswiss). To represent the major climatic regions of Switzerland, the hygrothermal analysis used in this study is applied for the following four geographic locations in Switzerland (Figure 4): Zurich, Geneva, Lugano and Davos. Zurich and Geneva are urban agglomerations north of the Alps; Lugano is a city south of the Alps; and Davos is a small Alpine town, located in the eastern Swiss Alps. The mean annual precipitations in Zurich, Geneva, Lugano and Davos are 1086, 971, 1545 and 1022 mm, respectively. The mean annual temperatures in Zurich, Geneva, Lugano and Davos are 8.8, 9.9, 11.9 and 3.9 °C, respectively.

Figure 4. The chosen four geographic locations in Switzerland (image: swisstop).

Hygrothermal models require the selection of representative climatic data as input. A common approach is to determine a moisture reference year from available long-term climatic data. A moisture reference year allows a correct evaluation of the moisture loading of a wall envelope. Hourly meteorological data from MeteoSwiss stations from the year 1981 to 2010 are used for the selection of the moisture reference year. The moisture reference year for analysis is selected based on the procedure proposed in Zhou *et al.* 2016 [20], which involves four steps:

1. Determination of the wall orientation with the largest Climatic Index [20] and calculation of the Climatic Index for the selected wall orientation for the whole set of considered years; the Climatic Index is based on comparing wetting load to drying potential, dividing the annual wind-driven rain load by the annual potential evaporation, as follows,

$$\text{Climatic Index} = \frac{\text{annual wind driven rain load}}{\text{annual potential evaporation}} \quad (7)$$

where the numerator represents the wetting component while the denominator represents the drying component. Therefore, a higher Climatic Index value indicates a higher moisture damage risk for the building envelope. Figure 5 shows Climatic Index rose for Zurich, Geneva, Lugano and Davos at different orientations in 1994. The orientation with the largest Climatic Index is found to be similar for all years for each of the cities. The orientation with the largest

Climatic Index is selected as it gives most severe moisture problems. The selected wall orientations are found to be 240, 240, 330 and 30 degrees from north, for Zurich, Geneva, Lugano and Davos, respectively (Figure 5).

2. Selection of three years around the top 10%-level Climatic Index for each city. For example, the three years with 10%-level Climatic Index for Zurich are 1993, 1999 and 2000, respectively.

3. Evaluation of the hygrothermal performance with simulations for the three selected years and determination of the related RHT Index values [26]; the RHT Index is a hygrothermal performance indicator based on the number of hours above threshold relative humidity and temperature values.

4. Selection among these three years of the year with the highest RHT value as the moisture reference year. The moisture reference years for Zurich, Geneva, Lugano and Davos are found to be 1999, 2006, 1993 and 1999, respectively.

Figure 5. Climatic Index rose for Zurich, Geneva, Lugano and Davos in 1994.

2.4 Initial and boundary conditions

The initial conditions for all building components are a uniform temperature of 20 °C and a relative humidity of 60%. The simulation is started from October 1st. The meteorological data are repeated for 8 years and the results of the 8th year, which are found to be independent from the initial conditions, are used for analysis. Hourly outdoor air temperature, relative humidity, wind speed, wind direction, solar radiation and horizontal rain are used to drive the hygrothermal model.

The exterior convective heat transfer coefficient ($h_{h,e}$) is set to be $4+4 \times V_v$ W/m² K according to European standard EN15026 (BS EN 15026, 2007), where V_v is the wind velocity. The exterior mass transfer coefficient ($h_{m,e}$) is related to the exterior convective heat transfer by use of the Lewis analogy: $h_{m,i} = h_{h,i} \times 7.7 \times 10^{-9}$. The calculation of net radiation at the exterior wall surface follows the one used in Janssen *et al.* 2007 [33]. The wind-driven rain load for different wall orientations is calculated according to ASHRAE Standard 160 - Criteria for Moisture Control Design Analysis in Buildings [37]. As proposed by Künzeli [34], we estimate that approximately 70% of the wind-driven rain hitting the façade stays there; the rest splashes off the surface and falls to the ground. Table 3 shows cumulative annual wind driven rain and irradiation for the selected orientations in the four cities.

Table 3 Cumulative annual WDR and solar irradiation for the selected orientations in the four cities

	Zurich	Geneva	Lugano	Davos
Annual cumulative WDR (kg/m ² /a)	551.6	539.5	409.6	392.2
Annual solar irradiation (kWh/m ² /a)	1023.9	1135.9	783.6	851.8

The interior conditions are determined according to the European standard EN15026 [38], in which indoor air temperature and relative humidity depend linearly on the outdoor temperature. This interior condition represents an indoor environment with small moisture load. The interior convective heat transfer coefficient ($h_{h,i}$) is set equal to 8.0 W/m² K. The interior mass transfer coefficient ($h_{m,i}$) is also related to the interior convective heat transfer by use of the Lewis analogy, as given above.

2.5 Hygrothermal performance evaluation criterion

The results from hygrothermal simulations are analyzed using a hygrothermal performance evaluation criterion, called the RHT Index [26]. The RHT Index indicates the risk of moisture-related problems and can be used to quantify and compare the hygrothermal responses of different parts of wall envelopes. The 10-day interval relative humidity, RH (%), and temperature, T (°C), are used to determine the RHT Index. The RHT Index is calculated as:

$$RHT = \sum (RH - RH_x) \times (T - T_x), \quad \text{for } RH > RH_x \text{ and } T > T_x \quad (19)$$

with threshold values set to be $RH_x = 80\%$ and $T_x = 5^\circ\text{C}$. The RHT Index evaluates the risk for moisture damage using the combined moisture and temperature response of a selected location in the building envelope. The degradation mechanism considered here is that of mold occurrence, possible at relative humidity larger than 80% and temperature larger than 5 °C. In this study, the location selected for RHT Index analysis is the interface between the original interior plaster and the aerogel insulation layer, as this is the most critical location in the case of a masonry wall with interior insulation.

3. Results

Considering the large number of wall assemblies studied, each combination is denoted using the following acronyms: the first letter represents the location of the city (Z: Zurich; G: Geneva; L: Lugano; D: Davos); the second part represents the type of wall structure (3B: wall structure with 3 wythes of brick; 2B: wall structure with 2 wythes of brick); the third part represents the type of render (LM: lime mortar; LP: lime plaster; LCP: lime cement plaster; MP: mineral plaster); the fourth part represents the type of brick (1: brick type 1; 2: brick type 2); the fifth part represents the type of vapor control strategy (W: with vapor barrier; O: without vapor barrier). As an example, Z-3B-LM-1-W refers to a wall envelope located in Zurich, composed of 3 wythes of brick of type 1, finished by a lime mortar render at the outside and with a vapor barrier at the inside of the interior plaster.

3.1 Influence of render

Figure 6 shows the RHT Index for different wall envelopes at the evaluation location, i.e. the masonry/aerogel plaster interface for the four regions. Among all the parameters, the capillary behavior of the render is the factor with most impact on the resulting RHT Index. Wall envelopes with the lime mortar with high capillary behavior show the largest RHT Indices. By comparison, the wall envelopes with less capillary active renders, such as lime cement plaster and mineral plaster, show very small RHT Indices. Figure 7 compares the relative humidity at the evaluation location for four wall envelopes with different renders for Geneva. The relative humidity in the wall envelopes with the capillary active renders (lime mortar and lime plaster) is above 90% year-round, whereas the relative humidity in the wall envelopes with less capillary active renders (lime cement plaster and mineral plaster) is most of the time below 80%. The use of capillary active renders with larger liquid permeability leads to higher moisture content in the building envelope. Moisture-related problems are therefore most likely in the wall envelopes with lime mortar or lime plaster renders, which both present a high capillary absorption coefficient.

Figure 6. RHT Index for different wall envelopes: (a) and (b) Wall envelopes with 3 and 2 wythes of brick for Zurich; (c) and (d) Wall envelopes with 3 and 2 wythes of brick for Geneva; (e) and (f) Wall envelopes with 3 and 2 wythes of brick for Lugano; (g) and (h) Wall envelopes with 3 and 2 wythes of brick for Davos. (LM: lime mortar; LP: lime plaster; LCP: lime cement plaster; MP: mineral plaster)

Figure 7. Comparison of RH for wall envelopes with different renders (G-3B-LM-1-O, G-3B-LP-1-O, G-3B-LCP-1-O and G-3B-MP-1-O in Geneva) at the evaluation location. (G represents Geneva; 3B represents wall structure with 3 wythes of brick; LM: lime mortar; LP: lime plaster; LCP: lime cement plaster; MP: mineral plaster; the number 1 represents brick type 1; O means vapor control without vapor barrier.)

3.2 Influence of wall structure: 3 versus 2 wythes of brick

The RHT Indices of envelopes with different wall structures are found to be quite close to each other (Figure 6). Compared to the influence of render on RHT Index, the influence of number of wythe on RHT Index is rather small. In general, envelopes with three wythes of brick show slightly smaller RHT Indices. The lower RHT Index for envelopes with three wythes of brick is mainly due to the lower relative humidity in these envelopes. Figure 8 compares the relative humidity and temperature for a wall envelope with different wall structures in Geneva. In effect, the wall envelope with three wythes of brick show smaller relative humidity values than the wall envelope with two wythes of brick. By comparison, the temperature difference between the two envelopes is very small. The smaller relative humidity in the wall with three wythes of brick is due to its larger thickness and thus larger moisture storage capability.

Figure 8. Comparison of RH and temperature at the evaluation location for a wall envelope with different wall structures in Geneva. (G represents Geneva; 3B represents wall structure with 3 wythes of brick and 2B represents wall structure with 2 wythes of brick; LP: lime plaster; the number 1 represents brick type 1; O means vapor control without vapor barrier.)

3.3 Influence of brick type: high versus low capillary behavior

The influence of brick type on RHT Index is complex. In general, wall envelopes with high capillary active bricks show larger RHT Indices compared to wall made of bricks with lower capillary behavior. For instance, the wall envelope G-3B-LP-1-O has a RHT Index value of 4864, whereas the wall envelope G-3B-LP-2-O has a RHT Index value of 1245. Figure 9 shows the comparison of the relative humidity and temperature at the evaluation location for the two wall envelopes. The two wall envelopes show very similar temperatures, whereas a large difference is observed in relative humidity. The wall envelope G-3B-LP-1-O with high capillary active brick shows larger relative humidity values than the wall envelope G-3B-LP-2-O.

We may conclude that a more capillary active brick will promote the redistribution of moisture towards the critical zone at the inside of the wall envelope, and may lead to a higher

risk of moisture problems. However, the influence of brick type depends also on the quality of the rain barrier by the rendering. When rain does not penetrate, capillarity is not effective.

Figure 9. Comparison of RH and T at the evaluation location for wall envelopes with different bricks in Geneva (G-3B-LP-1-O and G-3B-LP-2-O): (a) RH (b) temperature. (G represents Geneva; 3B represents wall structure with 3 wythes of brick; LP: lime plaster; the number 1 represents brick type 1 and the number 2 represents brick type 2; O means vapor control without vapor barrier.)

3.4 Influence of vapor control strategy: with and without vapor barrier

The influence of the vapor control strategy on RHT Index is found to depend highly on capillarity of the render. For wall envelopes with capillary active renders such as lime mortar and lime plaster, the presence of a vapor barrier leads to higher RHT Indices in the wall envelopes (Figure 5). By comparison, for wall envelopes with less capillary active render such as lime cement plaster and mineral plaster, the presence of a vapor barrier results in lower RHT Indices (Figure 5). Figure 10a compares the relative humidity for wall envelope with high capillary active render, without and with vapor barrier, G-3B-LP-2-O and G-3B-LP-2-W. For the wall envelope with vapor barrier, the relative humidity stays always above 98%, while the relative humidity remains between 75% and 95% for the wall envelope without va-

por barrier. During summer, the relative humidity even drops below 80%. This indicates that, for a wall envelope with high capillary active render, the moisture levels are lower in a wall without vapor barrier compared to the wall with vapor barrier. However, this observation changes for a wall envelope with a less capillary active render. Figures 10b indicates that the presence of a vapor barrier can lower relative humidity moderately during winter months. The increase of relative humidity during winter for the wall envelope without vapor barrier (G-3B-LCP-2-O) is found to be due to the occurrence of interstitial condensation. However, during summer, the wall envelope without vapor barrier shows lower values of relative humidity than the wall envelope with vapor barrier. This means that the wall envelope without vapor barrier can dry both to outside and inside during summer, leading to lower moisture levels in the masonry wall in the warm months. We may conclude that the influence of a vapor barrier depends on the capillary activity of the render. When the render is capillary active and higher moisture contents can be attained, it is beneficial to omit a vapor barrier allowing drying both to outside and inside. In the case of less capillary active renders, the presence of a vapor barrier can prevent interstitial condensation during winter. However, during summer, this vapor barrier prevents further drying of the wall.

Figure 10. Influence of vapor control strategy: (a) RH from wall envelopes G-3B-LP-2-W and G-3B-LP-2-O at the interface between original interior plaster and aerogel insulation layer (b) RH from wall envelopes G-3B-LCP-2-W and G-3B-LCP-2-O at the evaluation location. (G represents Geneva; 3B represents wall structure with 3 wythes of brick; LP: lime plaster; LCP: lime cement plaster; the number 2 represents brick type 2; O means vapor control without vapor barrier and W means vapor control with vapor barrier.)

3.5 Influence of climatic conditions

The impact of climatic conditions on hygrothermal performance of wall envelope is similar among Zurich, Geneva and Lugano (Figure 5). However, the RHT Indices for Davos have smaller values, due to the low temperatures in Davos during winter. The climate in Davos is much colder than the other 3 regions. For instance, the temperature at the evaluation location is mostly lower than 5°C in the winter period for the wall envelope D-3B-LM-1-O (Figure 10a). As a result, the RHT Index is 0 in these periods in Davos even though the relative humidity is above 80% (Figure 10b). In general, we may conclude that the influence of climatic conditions for different cities in Switzerland has a rather minor influence.

Figure 11. RH (a) and temperature (b) at the evaluation location from the wall envelope D-3B-LM-1-O. (D represents Davos; 3B represents wall structure with 3 wythes of brick; LM: lime mortar; the number 1 represents brick type 1; O means vapor control without vapor barrier)

Of significant relevance is the determination of the wind-driven rain load. Given the variation of rain deposition over a façade, as demonstrated with in-situ measurements (Kubilay et al. 2014) and with computational fluid dynamics (Kubilay et al. 2013, 2015, 2017), the single wind-driven rain load ratio used (as per TenWolde 2008 and Künzle [34]) in this study could be viewed as a simplification. However, the use of non-uniform wind-driven rain load over the façades would require two-dimensional if not three-dimensional analysis of the hygrothermal performance of the envelope assembly, where such studies are outside the scope of this study.

4. Influence of water leakage

The study indicates that the capillary behavior of the render is the most important factor influencing the hygrothermal performance of internally insulated masonry walls. Although a wall may show no sign of moisture problem before internal retrofitting, moisture problem

can occur after internal retrofitting. It is important to assess material properties of the render comprehensively before adding internal wall insulation to avoid potential moisture risk.

Even in presence of renders that are less capillary active, like mineral plaster, water still has possibilities to leak into the building envelope through cracks, faulty windows, inaccurate joints and openings, etc. Therefore, it is necessary to evaluate the potential risk related to such water penetration on hygrothermal performance. In this study, the water leakage into the wall envelope is modeled using the following approach proposed by the ASHRAE guideline 160 [37]: 1% of wind-driven rain load is assumed to leak in the assembly and to be deposited on the outside surface of the first wythe of brick that actually bypasses the render. Van Den Bossche et al. 2011 [39] indicated that assuming 1% of water leakage is a reasonable estimate based on their literature review. Figure 11a shows the relative humidity at the critical location for the wall envelopes with vapor barrier (Z-3B-MP-1-W) and without vapor barrier (Z-3B-MP-1-O) with water leakage. The relative humidity for the wall envelope with vapor barrier remains always above 80%. The drying capability towards outside environment in the warm period is not large enough to lower the relative humidity below 80%. By comparison, the relative humidity for the wall envelope without vapor barrier rises above 80% only in the cold months. The relative humidity drops below 80% in the warm months due to drying to both sides of the wall. The corresponding RHT Index for wall envelopes without and with vapor barrier are 1044.5 and 196.7, respectively. This indicates that the wall envelope with vapor barrier has higher risk of moisture problem compared to the wall envelope without vapor barrier when water leakage is considered. However, it is found that, when the water vapor resistance factor of the mineral plaster is reduced from 25 to 10, the relative humidity for the wall envelope without vapor barrier remains below 80%. By comparison, for the wall envelope with vapor barrier, lowering the water vapor resistance factor of the mineral plaster does almost not change the relative humidity. We may conclude that, when rain water leakage occurs, the presence of a vapor barrier may lead to high relative humidity values in the wall. Lowering the vapor resistance of the render may allow in this case a better drying to the outside.

463

464

465

466

467

468

469

Figure 12 (a) Relative humidity for the wall envelope Z-3B-MP-1-W and Z-3B-MP-1-O a) with 1% water leakage; (b) with 1% water leakage and vapor resistance factor of 10 for the mineral plaster. (Z represents Zurich; 3B represents wall structure with 3 wythes of brick; LM: lime mortar; the number 1 represents brick type 1; O means vapor control without vapor barrier and W means vapor control with vapor barrier)

470

5. Discussion and Conclusion

471

472

473

474

475

476

477

A new method is used in this study to select moisture reference year. The moisture reference year determines the hygrothermally critical climatic conditions for assessing the hygrothermal performance of building envelope. The selected moisture reference year considers the influence of both wetting and drying potentials on the wall envelope. Both wetting and drying potentials are indispensable environmental factors for the evaluation of the hygrothermal behavior of building envelopes. This improved selection of moisture reference years will lead to more reliable evaluation of moisture risks in the long run.

478

479

The data are analysed using the RHT Index as the threshold values of the RHT Index can be chosen taking into account a specific moisture degradation mechanism. For example,

the thresholds used for metal corrosion are a temperature above 0 °C and a relative humidity above 80% [40]. For comparison, decay of wood material occurs when the relative humidity is above 95% and the temperature above 0 °C [41]. Freeze-thaw damage could not be evaluated with RHT Index, as the freeze-thaw damage is affected by freeze-thaw cycles [42]. A critical RHT Index for relevant moisture damage mechanism could be determined by performing laboratory hygrothermal experiments, but such investigation would be outside the scope of this work. Nevertheless, the calculated RHT Index from hygrothermal simulation could then be compared with the critical RHT index to determine whether there is risk of moisture problem. The work performed here using the RHT Index allows to compare the behavior of the different walls exposed to different climates.

A main advantage of highly insulating materials used in energy retrofit situations is that the loss of inner space for the internal thermal insulation is greatly reduced, as seen with the aerogel-based high insulating plaster. The application of the aerogel-based high insulating plaster for internal retrofitting is shown to not necessarily lead to moisture problems. Render type, more specifically its liquid capillary behavior, has a much larger influence on the hygrothermal performance of internally insulated masonry than the other factors, such as climatic condition, wall structure, render type and vapor control strategy. For the wall envelope with less capillary active renders such as mineral plaster, the moisture risk is very low. When the render is more capillary active, such as a lime mortar or a lime plaster, the moisture risk of wall envelopes is very high. It is important to examine carefully the liquid capillary behavior of render before conducting internal retrofitting projects.

For wall envelope with relatively high capillary active renders, it is suggested to not use vapor barrier for retrofitting with interior insulation. By comparison, for wall envelope with less capillary active renders, whether or not to use vapor barrier depends mainly on the risk of water leakage and vapor resistance factor of the render. Therefore, for the climates considered here and for the wall envelope with less capillary active renders, if the risk of water penetration in the building envelope is high and the vapor resistance factor of the renders is high, it is safer not to use a vapor barrier between the insulation layer and the original wall. The accumulated moisture in the wall envelope can then dry additionally to the inside environment in

the warm period. If the risk of water penetration in the building envelope is low or the vapor resistance factor of the render is low, it is favorable to apply a vapor barrier between the insulation layer and the original wall to stop interstitial condensation in the cold period.

For a real case analysis of moisture risk problem for buildings after internal retrofitting, it is important to perform CFD based calculation for accurate distribution of wind-driven rain intensity. Facade features and nearby buildings influence rain deposition significantly [43]. The WDR load at different locations of a wall could be very different and thus moisture source to the wall envelope will be very different. Even though the render of the wall envelope is very capillary active, the risk of moisture problem of wall envelope could be low due to low WDR load caused by sheltering from nearby buildings.

Acknowledgment

The research presented in this paper is supported in part by funds from the Swiss Competence Center for Energy Research project “Future Energy Efficient Buildings and Districts”, CTI.1155000149.

References

- [1] IEA(International Energy Agency). Transition to Sustainable Buildings Strategies and Opportunities to 2050. 2013. Paris, France.
- [2] Straube J, Schumacher C. Interior insulation retrofits of load-bearing masonry walls in cold climates. *J Green Build.* 2007;2:42-50.
- [3] Vereecken E, Roels S. A comparison of the hygric performance of interior insulation systems: A hot box-cold box experiment. *Energ Buildings.* 2014;80:37-44.
- [4] Vereecken E, Roels S. Capillary active interior insulation: do the advantages really offset potential disadvantages? *Mater Struct.* 2015;48:3009-21.
- [5] Pavlik Z, Cerny R. Hygrothermal performance study of an innovative interior thermal insulation system. *Appl Therm Eng.* 2009;29:1941-6.
- [6] Toman J, Vimmrova A, Cerny R. Long-term on-site assessment of hygrothermal performance of interior thermal insulation system without water vapour barrier. *Energ Buildings.* 2009;41:51-5.
- [7] Haupl P, Jurk K, Petzold H. Inside thermal insulation for historical facades. 2003:463-9.
- [8] Johansson P, Geving S, Hagentoft C-E, Jelle BP, Rognvik E, Sasic Kalagasidis A, et al. Retrofitting a brick wall using vacuum insulation panels: measured hygrothermal effect on the existing structure. In: *Proceedings of the 10th Nordic Symposium on Building Physics*, Lund, Sweden, June 15-19, 2014.
- [9] Kehl D, Ruisinger U, Plagge R, Grunewald J. Wooden beam ends in masonry with interior insulation-A literature review and simulation on causes and assessment of decay. In: *Proceedings of 2nd Central European symposium on building physics*, Vienna, Austria, September 9–11, 2013.

- [10] Kloseiko P, Arumagi E, Kalamees T. Hygrothermal performance of internally insulated brick wall in cold climate: A case study in a historical school building. *J Build Phys*. 2015;38:444-64.
- [11] Morelli M, Scheffler GA, Nielsen TR, Svendsen S. Internal insulation of masonry walls with wooden floor beams in northern humid climate. In: *Thermal performance of the exterior envelopes of whole buildings XI*. Clearwater Beach, Florida, USA, December 5–9, 2010. pp. 1-11
- [12] Ueno K, Straube J, Van Straaten R. Field Monitoring and Simulation of a Historic Mass Masonry Building Retrofitted with Interior Insulation. In: *Proceedings of the Thermal Performance of the Exterior Envelopes of Whole Buildings XII International Conference*, Clearwater Beach, Florida, USA, December 1-5, 2013. pp. 306-321
- [13] Nielsen A, Møller EB, Rasmussen TV, Hansen EJdP. Use of sensitivity analysis to evaluate hygrothermal conditions in solid brick walls with interior insulation. In: *Proceedings of the 5th International Building Physics Conference*, Kyoto, Japan, May 28–31, 2012. pp. 377-84.
- [14] Zhao JH, Grunewald J, Ruisinger U, Feng S. Evaluation of capillary-active mineral insulation systems for interior retrofit solution. *Build Environ*. 2017;115:215-27.
- [15] Andersson A. Additional thermal insulation of existing buildings. Technical consequences. In: *Proceeding 5 th International Brick Masonry Conference*, Washington DC, USA, October 5-10;1982.
- [16] Mukhopadhyaya P, Kumaran M, van Reenen D. Vapour barrier and moisture response of wood-frame stucco wall—results from hygrothermal simulation. *CIB World Building Congress 2004*, Toronto, Ontario, Canada, May 2-7, 2004. pp. 1-10.
- [17] Tariku F, Simpson Y, Iffa E. Experimental investigation of the wetting and drying potentials of wood frame walls subjected to vapor diffusion and wind-driven rain loads. *Build Environ*. 2015;92:368-79.
- [18] Karagiozis AN, Lstiburek J, Desjarlais A. Scientific analysis of vapor retarder recommendations for wall systems constructed in North America. In: *Proceedings of thermal performance of the exterior envelopes of buildings X*, Clearwater, FL, USA; 2007.
- [19] Johansson P, Time B, Geving S, Jelle BP, Sasic Kalagasidis A, Hagentoft C-E, et al. Interior insulation retrofit of a brick wall using vacuum insulation panels: design of a laboratory study to determine the hygrothermal effect on existing structure and wooden beam ends. In: *Proceedings of the 12th International Conference on Thermal Performance of the Exterior Envelopes of Whole Buildings*, Clearwater Beach, Florida, December 1-5, 2013.
- [20] Zhou XH, Derome D, Carmeliet J. Robust moisture reference year methodology for hygrothermal simulations. *Build Environ*. 2016;110:23-35.
- [21] Blocken B, Carmeliet J. A review of wind-driven rain research in building science. *J Wind Eng Ind Aerod*. 2004;92:1079-130.
- [22] Choi EC. Variation of wind-driven rain intensity with building orientation. *J Arch Eng*. 2000;6:122-8.
- [23] Guizzardi M, Carmeliet J, Derome D. Risk analysis of biodeterioration of wooden beams embedded in internally insulated masonry walls. *Constr Build Mater*. 2015;99:159-68.
- [24] Künzle HM, Künzle H, Holm A. Rain protection of stucco facades. *ASHRAE*. 2004.
- [25] Pazera M, Bomberg M. Applying lessons from clay–brick veneer to design a stucco mix. *BEST Conference Building Enclosure Science & Technology*, Portland, USA, April, 2010.
- [26] Kumaran M, Lackey J, Normandin N, van Reenen D, Tariku F. Summary report from task 3 of MEWS project at the Institute for Research in Construction-Hygrothermal properties of several building materials. *National Research Council*, Ottawa, Canada; 2002.
- [27] Larsen PK, Hojskoie DT. Moisture physical properties of bricks. *Technical Report*. Technical University of Denmark. 1995;1-37.

- [28] Stahl T, Brunner S, Zimmermann M, Ghazi Wakili K. Thermo-hygic properties of a newly developed aerogel based insulation rendering for both exterior and interior applications. *Energ Buildings*. 2012;44:114-7.
- [29] Ibrahim M, Biwole PH, Wurtz E, Achard P. A study on the thermal performance of exterior walls covered with a recently patented silica-aerogel-based insulating coating. *Build Environ*. 2014;81:112-22.
- [30] Aspen A. Spaceloft Subsea data sheet. 2011.
- [31] Liu ZH, Ding YD, Wang F, Deng ZP. Thermal insulation material based on SiO₂ aerogel. *Constr Build Mater*. 2016;122:548-55.
- [32] White SO, Zafiropoulos NA, Clark JL. Aerogel insulation panels and manufacturing thereof. US Patent 9,593,206, 2017.
- [33] Janssen H, Blocken B, Carmeliet J. Conservative modelling of the moisture and heat transfer in building components under atmospheric excitation. *Int J Heat Mass Tran*. 2007;50:1128-40.
- [34] Künzle HM. Simultaneous heat and moisture transport in building components [PhD thesis]. University of Stuttgart 1995.
- [35] Guizzardi M. Hygrothermal performance assessment of novel interior insulation solutions [PhD thesis]. ETH Zürich, Switzerland; 2014.
- [36] Hagetoft C-E, Kalagasidis AS, Adl-Zarrabi B, Roels S, Carmeliet J, Hens H, et al. Assessment method of numerical prediction models for combined heat, air and moisture transfer in building components: benchmarks for one-dimensional cases. *J Therm Envel Build Sci*. 2004;27:327-52.
- [37] TenWolde A. ASHRAE Standard 160 P-Criteria for Moisture Control Design Analysis in Buildings. *ASHRAE Transactions*. 2008;114:167-71.
- [38] EN-15026. Hygrothermal performance of building components and building elements - Assessment of moisture transfer by numerical simulation. 2007.
- [39] Van Den Bossche N, Lacasse M, Janssens A. Watertightness of masonry walls: an overview. In: *Proceedings of the 12th international conference on durability of building materials and components*, Porto, Portugal, April 12–15, 2011, pp. 49–56.
- [40] Garverick L. Corrosion in the petrochemical industry: ASM international; 1994.
- [41] Viitanen H, Toratti T, Makkonen L, Peuhkuri R, Ojanen T, Ruokolainen L, et al. Towards modelling of decay risk of wooden materials. *Eur J Wood Wood Prod*. 2010;68:303-13.
- [42] Zhou XH, Derome D, Carmeliet J. Hygrothermal modeling and evaluation of freeze-thaw damage risk of masonry walls retrofitted with internal insulation. *Build Environ*. 2017;125:285-98.
- [43] Kubilay A, Carmeliet J, Derome D. Computational fluid dynamics simulations of wind-driven rain on a mid-rise residential building with various types of facade details. *J Build Perf Sim*. 2017;10:125-43.

Highlights

This paper studies the influence of envelope properties on interior insulation solutions for masonry walls for different climatic conditions in Switzerland.

The influence of masonry structure and brick type on envelope hygrothermal performance is much smaller than the one of the exterior finishing render.

For wall envelopes with less capillary active renders, the need to use a vapor barrier depends on the risk for water leakage and the vapor resistance of the render.