Hygrothermal performance of internally insulated brick wall in cold climate: field measurement and model calibration

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ABSTRACT: The interior thermal insulation is frequently one of the only possible solutions for thermal upgrade of the building envelope where the external appearance cannot be changed. In this study four insulation materials were used to build up in-situ test walls. The indoor climate in the test room was controlled to simulate the typical living space with high moisture load. The temperatures, relative humidity and heat flows were monitored. The measurement results over nine months were used to analyse the hygrothermal performance of four different insulation materials.
The hygrothermal behaviour of insulation materials during drying and wetting period are presented. The results show that timing of the renovation works is a matter of consideration to avoid the hygrothermal risks inside the retrofitted wall assemblies. The results show that in all the cases, thermal comfort can be improved by increasing the inner surface temperature and decreasing thermal conductivity. However, in some cases the risk of mould growth and interstitial condensation were present inside the retrofitted wall assemblies.

1 INTRODUCTION

During the last years, the campaigns have promoted and explained the need to save energy in buildings. The improvement of existing buildings has raised people's awareness of the energy consumption.

The surviving historic buildings are forming well-preserved areas in all the larger cities in Estonia. These areas are nominated as milieu valuable areas and are protected by planning laws. The main focus is on the built-up environment and therefore the preserving the exterior of the buildings is essential.

The simplest way to save energy in apartment buildings is to improve the building envelope by lowering the heat losses through the existing walls, ceiling and windows. By improving the building envelope with additional thermal insulation, it is possible to save energy and increase thermal comfort. Adding insulation to the external walls is used as a common solution. That can be easily used to lower the heat losses through the existing exterior walls if the buildings have no restrictions because of the architectural and historical values and the exterior can be changed.

In historic buildings, often the architectural and historic values set limitations to the use of external thermal insulation. Due to the regulations no changes outside the external wall on the facade are allowed to be done in the buildings with architectural and historic values. There exists a strong pressure to use internal insulation as a energy conservation measure in historic buildings.

Maurenbrecher (1998) monitored hygrothermal performance of an internally insulated 765 mm thick masonry wall. As a result of the renovation, the thermal resistance of the wall increased by 47 to 63%. The temperature between the insulation layer and masonry drops below freezing temperature for several months in the winter. Nevertheless the moisture levels did not seem to be a problem in the monitored wall sections.

Hens (1998) studied the hygrothermal performance of masonry walls insulated on the inside face and indicated that it increased the thermal bridging effect of partition walls, which resulted in much lower thermal resistance than that calculated.

Today's living habits cause higher indoor air humidity and therefore structures face larger humidity loads. Using correctly dimensioned vapor barriers can prevent the water vapor penetration to the construction. However, the quality of the installation is not always guaranteed and therefore the risk potential remains.

In addition of limiting the water vapour diffusion into structures, another possibility exists to use capillary active insulation materials. With these materials is possible to decrease initiation of moisture problems and can upgrade the thermal resistance of the existing walls (Scheffler 2003). Stopp (2001) found that with new materials and new technologies inside insulation can be a viable method. The authors preferred calcium silicate because this material can distribute the liquid moisture content in the structures, and, therefore, it accelerates the drying out process.

Häupl (2003, 2004) demonstrated the function of the insulation systems by presenting the measurement results of several internal insulation systems at a number of different outside wall construction. The application of capillary active inside insulation materials proved advantageous for the drying process of potential built-in moisture as well as for the limitation of the condensation amount during winter. The thermal transmittance of the building walls could approximately be halved in the presented cases without the necessity of vapour barriers. Toman (2009) presented long-term on-site assessment of hydrophilic mineral wool insulation system without water vapour barrier. The reconstructed building envelope exhibited very good hygrothermal performance. Nevertheless Morelli (2010) made computational analysis of the internal insulation solution of masonry walls with wooden floor beams in northern humid climate and showed that the solution would almost halve the heat loss through the wall section compared to the original one but the internal insulation reduces the drying potential of the wall which can lead to moisture problems.

Scheffler (2011) introduced an innovative and sustainable internal insulation system based on a light-weight autoclaved aerated concrete. The results showed that though the moisture content inside the masonry structure increased, the overall moisture level was kept below critical value.

Vereecken (2011) made hygrothermal comparison between capillary active and traditional vapor tight interior insulation system. The performance of the capillary active system is shown to be more sensitive to the different parameters (wind-driven rain load, orientation, catch ratio, finishing coat, thickness of the wall, etc). Additionally, there exists a large number of uncertainties concerning internal insulation (Nielsen 2011, Zhao, J. 2011).

Most of these computational and experimental studies have focused on wall structures in Central European climate conditions. In cold climate, external thermal insulation is hygrothermally a much safer solution than internal thermal insulation. Frequently, in hygrothermal performance risks arise. To avoid the possible mold growth and condensation problems special attention should be paid during the design and installation phase of the renovation solution.

A better understanding of the hygrothermal performance of the interior insulation retrofit approach in cold climate is needed. In this study, four solutions of internal thermal insulation for the brick wall are tested. An analysis was carried out to assess the impact of an interior insulation retrofit on the hygrothermal performance of a brick wall. The paper describes the test wall setup, presents measurement results over one year and the validation of numerical simulation models.

2 METHODS

Field measurements on a school building (Figure 1) and computer simulations were used in this study.

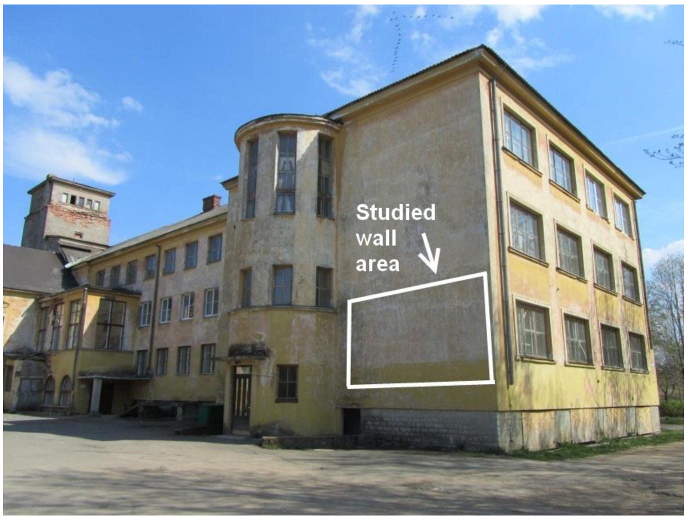

Figure 1. View of the studied school building.

2.1 *Field measurements*

To compare the hygrothermal performance of different internal insulation materials the same wall was insulated with four materials. Materials were selected so that diffusion open, capillary active, and vapour tight materials were used:

- calcium silicate (CaSi): capillary active material with very high open porosity and low vapour diffusion resistance;
- aerated concrete (AAC) with high open porosity, lower capillary activity and thermal conductivity;
- polyurethane board with capillary active channels (IQ-T) - combines low thermal conductivity and a certain capillary activity;
- polyisocyanurate board (PIR) with closed pores: low thermal conductivity and relatively high vapour diffusion resistance forming a vapour barrier in itself.

The original brick wall was 73…75 cm thick, composed of three layers of brick with two air and insulation (peat) layers between them. The thickness of the insulation layer was selected to represent typical products and to avoid large thermal transmittance differences between the walls.

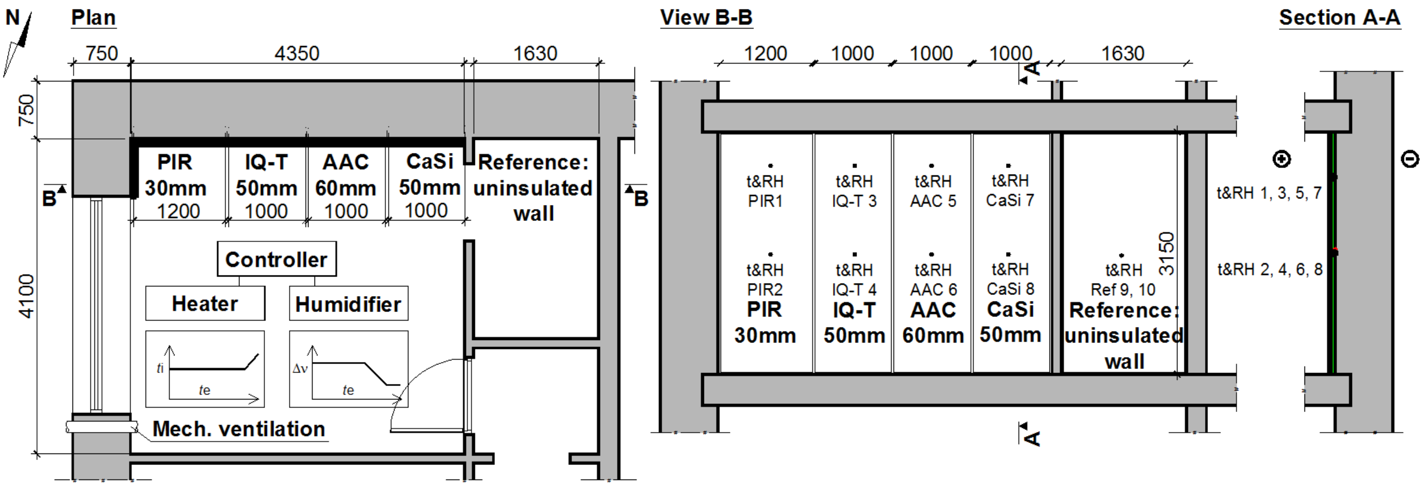

Figure 2. Plan, view, and section of the studied test walls.

Each test wall was equipped with two temperature and relative humidity (RH) sensors between insulation and the original wall (∅ 5mm, Rotronic HC 2 SC05) and heat flow plates (Hukseflux HFP01) on the internal surface of insulation. Internal and external surface temperatures were also measured.

Indoor climate was heated with the set point of thermostat +21 ºC and humidified to keep the moisture excess of +2.3…+4.4 g/m^3. Indoor climate conditions were selected to represent the average conditions in dwellings with high humidity loads (Kalamees et al. 2012), see Figure 4.

The climatization of the test room started by an attempt to imitate a typical renovation process:

– Period 1 (P1): internal insulation works and starting to heat the room: 27.03.2012; Δν +0.1 g/m^3 (not humidified);
– Period 2 (P2): starting to humidify ~3 months after installation (4.07.2012) to represent time period between the renovation and moving back in, high humidity load; Δν +2.3 g/m^3 (humidified).
– Period 3 (P3): humidifying period to see the influence of different humidity loads on hygrothermal performance of test walls, medium high humidity load: 4.07.2012…8.10.2012; Δν +2.9 g/m^3 (humidified)
– Period (P4): medium humidity load, 8.10.2012-14.12.2012; Δν +4.2 g/m^3 (humidified).
– Period 5 (P5): with low humidification (from 14.12.2012) to see drying out potential of different walls; Δν +2.5 g/m^3 (humidified according to indoor RH)

To assess the conditions favourable for mould growth the Finnish mould growth model (Viitanen 2007, 2010) was used. Critical RH levels RH_{crit}>80% and RH_{crit}>95% depending on substrate category was used. RH_{crit}>80% in case of PIR was used, because the side which is in contact with the original wall is covered with paper. RH_{crit}>95% for stone materials (CaSi and AAC) and IQ-T was used.

2.2 *Computer simulations*

The results of temperature and humidity measurements from test walls were compared in an 1D model with a commercial hygrothermal simulation program DELPHIN 5.7.4 (Grunewald 1997, 2000, Nicolai 2008). There were two main reasons for that comparison:

– to acquire a better understanding of the hygrothermal performance of the internally insulated brick walls;
– to validate the simulation model for future simulations with different initial and climatic conditions as well as with different dimensions of the building envelope.

The material producer's data and simulation program's (DELPHIN) material libraries were used to provide material properties. The density and porosity of original brick were measured. Brick with similar material properties was selected from DELPHIN's material library. The dependency of hygrothermal properties on the environmental conditions was taken into account: water vapour permeability, liquid water conductivity, thermal conductivity dependent on water content of a material. The main properties of materials, used in study are shown in Table 1.

Table 1. Properties of insulation materials

Property	Material			
	PIR	IQ-T	AAC	CaSi
Thickness of used layer, mm	30	50	60	50
Density, kg/m^3	32-38	45	90	360
Thermal conductivity λ, W/(mK)	0.027	0.031	0.047	0.063
Vapor diffusion resistance coefficient μ, -	100	27	2	4.6
Water absorption coefficient A_w, kg/(m^2 h$^{0.5}$)	1.0·10^{-7}	0.01	0.1	1.17

3 RESULTS

3.1 *Climate conditions*

Indoor and outdoor temperatures as well as temperatures between the insulation and the original wall are shown in Figure 3. Outdoor air temperatures fluctuated from +17 to +30°C in July with an average of +19.4°C. Temperature until December was rather mild, with an average temperature of +5.4°C in November and minimum temperatures reaching +1°C on a number of occasions.

According to Künzel (2011) freezing should be avoided to prevent damage to the materials. Although the outdoor air temperature stayed under -10°C for 8 days in December, none of the sensors detected temperatures below 0°C between the insulation systems and original wall.

Conditioned indoor temperature stayed the same throughout the heating period (+21+/-0.5°C). A drop (minimum of +17.5°C) of the indoor temperature during the cold period in December was caused by low power setting of additional heating in the room.

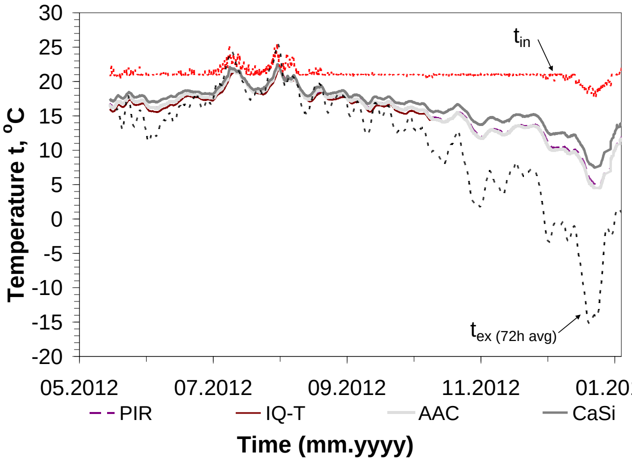

Figure 3. Temperatures between insulation systems and original wall and indoor/outdoor air temperatures.

Figure 4 shows the values of moisture excess plotted against exterior temperature. On the graph, different periods of humidification can be identified. Average values of moisture excess were 0.1 g/m^3, 2.3 g/m^3, 2.9 g/m^3, 4.2 g/m^3 and 2.5 g/m^3 for periods 1-5 respectively. Figure 8 to Figure 11 show the duration of the periods.

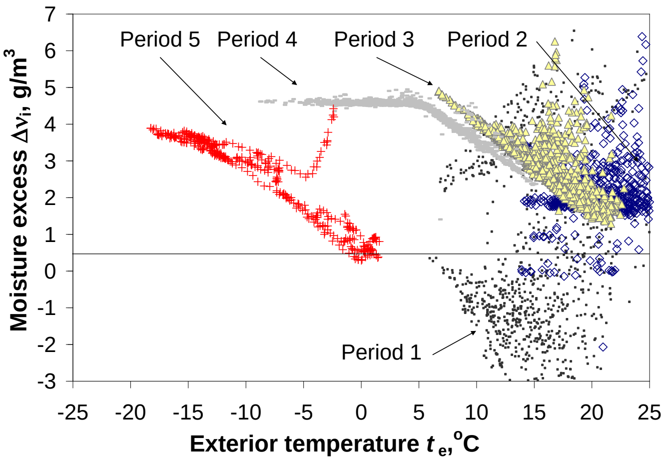

Figure 4. Indoor moisture excess dependent on exterior temperature.

3.2 *Comparison of reactions to changes in climate conditions*

Comparisons of relative humidities during the period without humidification (Period 1) of the test walls are given in Figure 5. Drying out period finished fastest in the case of CaSi (24 days), AAC section dried to the same level in 38 days, whereas iQ-T reached the lowest RH of 86% at the start of humidification (3 months after the installation).

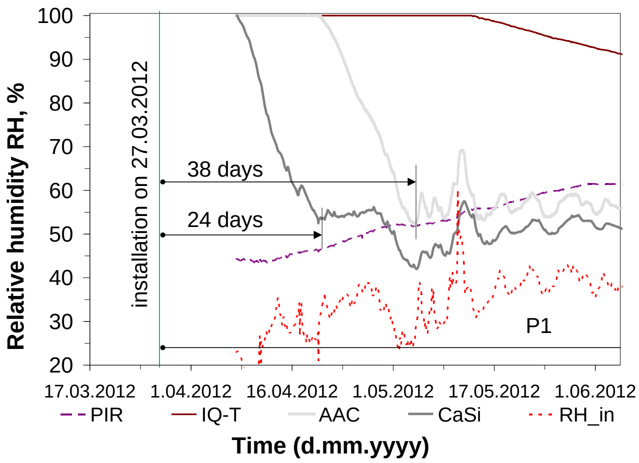

Figure 5. Drying period without humidification – relative humidities between insulation systems and original wall; time taken by wet systems to reach stable level.

Figure 6 shows the period of the start of humidification (transition from period 1 to 2). Two distinct behaviours are apparent – in the case of low vapour diffusion resistance (AAC, CaSi), the RH level behind the insulation follows the indoor conditions closely. PIR and iQ-T, on the other hand, reacted more slowly.

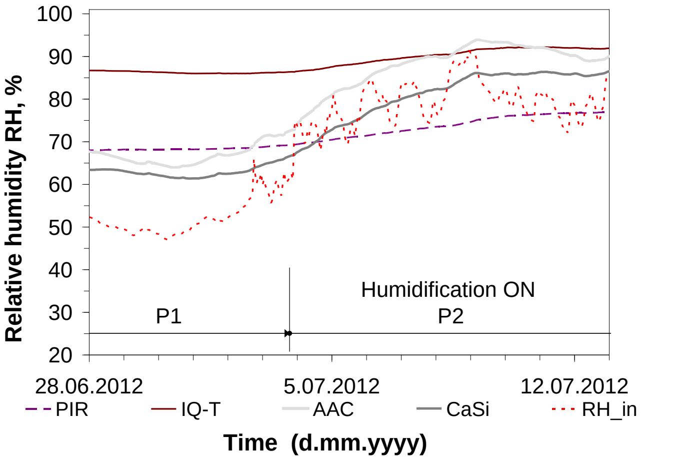

Figure 6. Start of humidification - relative humidities between insulation systems and original wall.

Second period of drying (period 5) is visible in Figure 7, permeable materials stabilize in about 5 days.

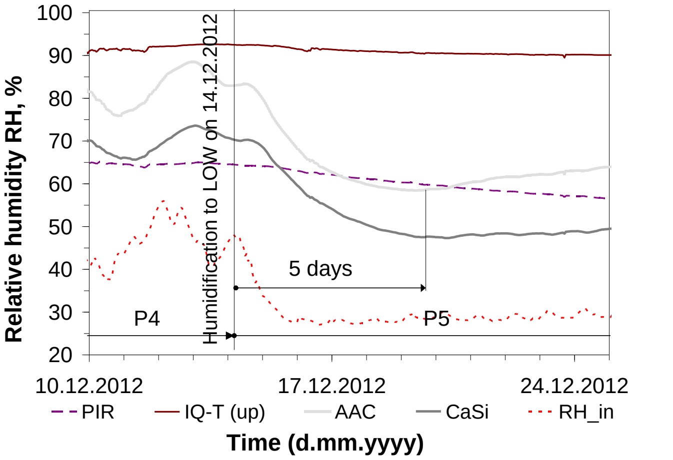

Figure 7. Drying period with no humidification – relative humidities between insulation systems and original wall. Time for permeable materials to reach stable level.

3.3 *Moisture-performance of the test walls*

3.3.1 *Relative humidity between the insulation and the original wall*

Relative humidity behind the insulating layer and the surface of the original wall fro different walls are given in Figure 8 to Figure 11. These charts also show the corresponding value of the relative humidity as simulated in Delphin and the assessment criteria for the proper hygrothermal performance.

Figure 8 exhibits the relative humidity of the PIR test wall. . Measured values of the relative humidity exceeded the critical limit (RH~80%) for 78 days of the 230 of the test duration. Both the measured and simulated humidities dropped to safer levels during period 4, while the lack of humidification (second half of December 2012) lowered it even further.

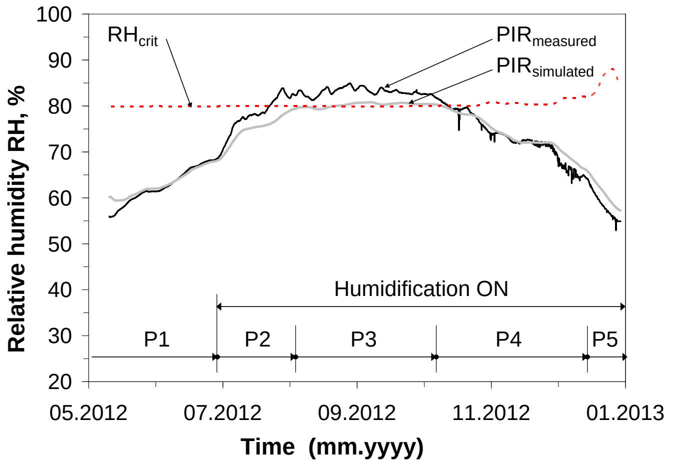

Figure 8. Relative humidity between PIR board and original wall; periods of humidification.

Figure 9 shows the relative humidity between the IQ-T insulation system until the error of the measurement system. The value of RH stayed just below the limit of 95% which is also the region where the capillary transport of humidity increases significantly. As a reference, the RH of the sensor close to the ceiling (IQ-T_{high}) is given.

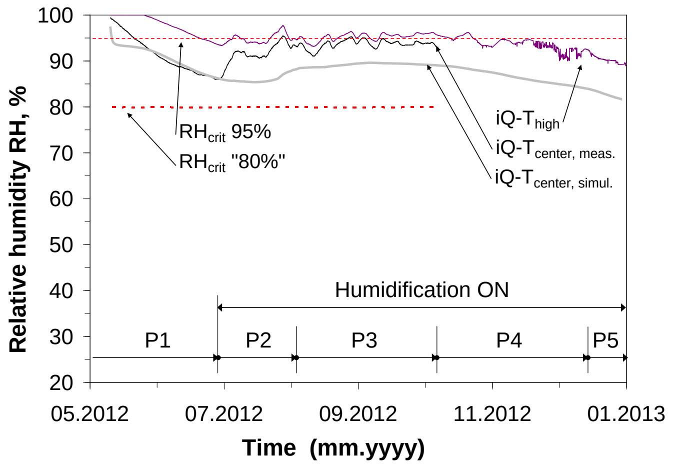

Figure 9. Relative humidity between iQ-T insulation system and original wall; periods of humidification.

Relative humidity behind the layer of AAC (Figure 10), due to its low water vapour diffusion resistance, reacted more quickly and drastically to the changes of indoor humidity. The period with higher moisture excess resulted in 59 hours of possible condensation.

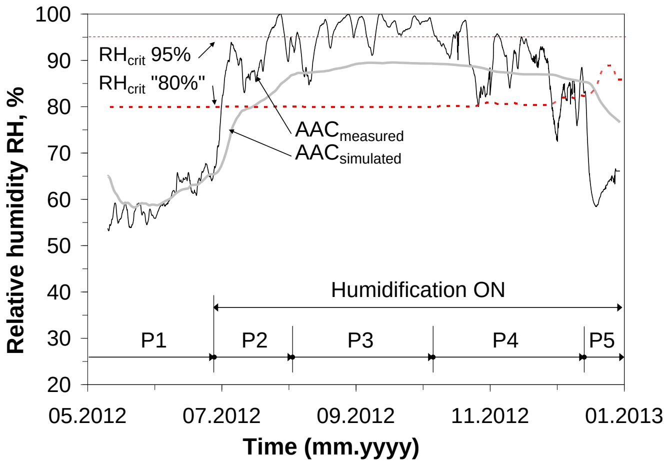

Figure 10. Relative humidity between AAC insulation system and original wall; periods of humidification.

Likewise to the AAC wall segment, the RH graph of CaSi (Figure 11) exhibits high fluctuations which follow the changes in the indoor relative humidity. However, the overall level stays lower with the maximum value of 95% during period 3. This is due to lower insulation thickness and higher thermal conductivity which leads to higher temperatures behind the insulation, while the absolute humidities stay practically on the same level.

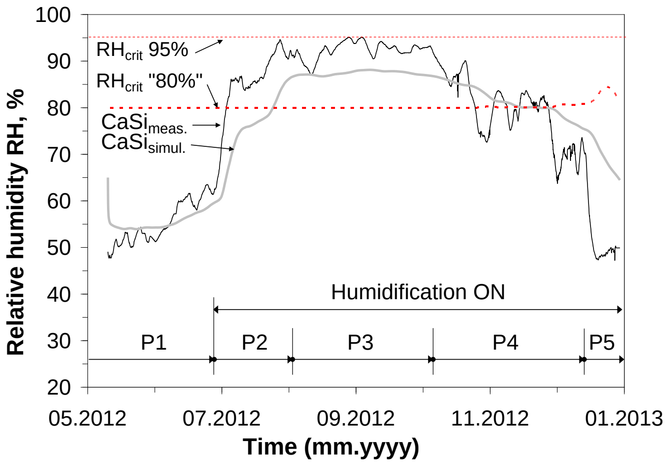

Figure 11. Relative humidity between CaSi insulation system and original wall; periods of humidification.

3.3.2 *Thermal conductivity and surface temperature*

Thermal transmittance was calculated based on heat flow and surface temperature measurements for the period of 1.09.2012-28.12.2012. The period was chosen with low temperature fluctuations and solar radiation. The average values for thermal transmittance are given in Figure 12.

Higher water vapour content was found to have an inconsiderable effect on the thermal transmittance, as the moist values of all materials dropped ~3% during the period without humidification. This is quite unexpected as the reduction of the moisture content of the vapour permeable materials was more significant than on the PIR.

The average values of surface temperature in November stayed within 19.2-19.8°C and the average for the uninsulated reference wall was 17.3°C (average indoor temperature 20.9°C). During the cold period in December, the surface temperature of the reference wall dropped to an average of 13.1°C, while the sections with insulation stayed 3-4°C higher (average indoor temperature 19.0°C) depending on the material.

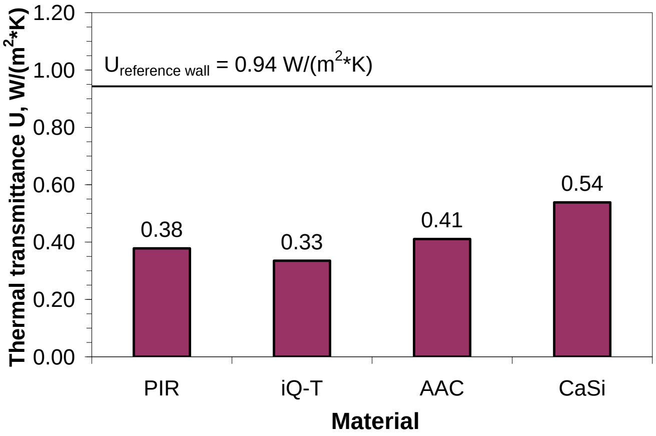

Figure 12. Average thermal transmittances calculated from measured thermal resistances of reference wall and insulation layers during the period of 1.09.2012-28.12.2012.

4 DISCUSSION

The hygrothermal performance of four internally insulated test walls was compared in field conditions. 1000mm wide sections of thermal insulation systems were installed on the same wall in the test room. Because of the possible moisture and heat flux between the test wall sections the different parts were separated by 50 mm wide joints. In the existing wall the ~50 mm deep grooves were cut and cleaned. Afterwards the joints in the existing wall and between the different insulation sections were completed with aluminium foil and polyurethane foam. Although there may have been some minor leaks between the test walls, the potential for the vapour diffusion and heat conduction was low and possible heat and moisture movement between the test walls was probably minor. Another factor influencing the accuracy of direct comparison between the wall sections could be non-uniform distribution of insulation in the existing wall and air flows in cavities. This may be considered as general limitation of the field study.

The temperatures measured in all the different insulation material sections and in reference wall section, of the brick façade were uniform. Façade temperature is mainly influenced by the outdoor temperature. The test wall is facing north, therefore the solar heat absorption was minimal. The uniform temperature can be explained by the relatively thick wall construction (typical thickness of external brick walls is 43…51 cm) and the different layers inside the wall that equalize the temperature distribution. The bigger temperature differences were on the surface of the inner face of the existing masonry wall. Largest temperature drop in the added insulation material was in case of the IQ-T and lowest in case of the CaSi, because of the difference in thermal transmittance. This result coincides with expected results.

Freeze-thaw damage mechanism can occur at temperatures well below freezing when the wall construction is essentially saturated. With brick walls, the limit for freezing can be lower than 0ºC because of the dissolved salts in the brick pores. The temperature limit can be from 0 to -5 ºC (Vesikari 1998). The temperatures inside the wall assemblies were measured between the added insulation material and existing wall. In all the cases the temperature did not drop below the freezing temperature between the insulation and existing wall. During the first year no freeze-thaw cycles were observed directly behind the insulation even if the limit was set to 0 ºC.

The lowest RH is with the PIR (dry installation) and the highest with the AAC (wet installation and vapour permeable material). During the installation of PIR no extra moisture is added to the wall and the RH between the insulation material and existing wall reflects the built in moisture of the existing wall. All the other materials were installed using glue-mortar and additional moisture was added to the construction that contributes to higher RH level.
As all wet materials had ~5 mm layer of glue mortar according to installation instructions, the amount of water added to the wall was largely the same. With IQ-T, the topmost plaster level was thicker than on the others (10-15 mm vs 2 mm with the CaSi and 5 mm with AAC). The moisture added during the retrofit works can cause long periods of high RH, if the renovation works are done during the period when the outdoor and indoor conditions are not suitable for the drying out or the moisture is not dried out before the rooms are taken into use again. The results show that timing of the renovation works or the start point of the reuse need to be taken into account. The time after the renovation works is most critical for the IQ-T, for CaSi and AAC it is considerably shorter. It is also significant, that although more resistant to vapour diffusion, humidification also rises the RH behind PIR layer.

To simulate the use of the room as a living space the humidifier and ventilation system were switched on two months after the installation of the insulation material layers. After switching on and off the humidifier, a much quicker response of the vapour open materials to the change than that of vapour tight materials was observed. Also, there is a difference in drying rate of the materials if two time periods are compared (period 1 and 5). The drying is accelerated because of the lowered moisture load and mechanical ventilation during period 5.

The measurement results show high humidity levels in all the cases. In the case of AAC, possible condensation occurred. The conditions suitable to initiate the mould growth are described in (Viitanen 2007, 2010). The measured temperature and RH results show that the conditions suitable for the mould growth were fulfilled during most of the time period. The most critical are the conditions in case of the PIR (RH_{crit}>80%) and AAC (RH_{crit}>95%).

The important aspect of any retrofit is the increase in thermal resistance of the building envelope. This results in reduced energy usage and improved thermal comfort for inhabitants. The thermal resistance was calculated using measured temperature difference across the brick wall, the insulation layers and the heat flow through the wall. Regarding the wall construction, the additional insulation resulted in a decrease of the thermal transmittance of the wall by 40 to 65%. The highest thermal resistance was achieved with IQ-T. There was evident temperature difference on the surface of the wall on the room side. During the winter period the temperature of the inner surface of the IQ-T wall was almost 3ºC higher than that of the reference wall. In all the cases, the temperature was higher than that of the reference wall and the thermal comfort was improved.

The quality of the simulation results depends on the input variables, on the assumptions and simplifications made and on simulation settings. Simulations of hygrothermal performance using the HAM-simulation programs may contain different kinds of errors, for instance, the description of the existing wall assemblies in terms of the chosen material properties with retrofitted building constructions. No thorough laboratory tests were conducted to obtain data about the properties of the different building materials used in the existing wall construction. The material database of the simulation tool and material data from the literature was used. Therefore, the field measurements enable us to check the accuracy of the simulation model.

The simulation models of four internally insulated brick walls were validated using field measurements. A satisfactory correlation between the calculated results and measured values was achieved.

The simulation models will be used for further studies to analyse the hygrothermal performance of different brick wall constructions with internal thermal insulation in the measured climate conditions and different outdoor and indoor climate conditions.

5 CONCLUSIONS

Upgrading of energy performance for existing historic buildings is often possible only by internal insulation. The study concentrated on four different materials. In-situ measurements in the test room with regulated indoor climate were conducted. The results show that the added moisture during installation can cause high RH levels in a wall for a long time period that can lead to interstitial condensation. The temperature and RH condition inside the wall between the added insulation and brick wall favouring mould growth were fulfilled during most of the time period.

As PIR board exceeded the $RH_{crit"80"}$ convincingly, it cannot be recommended to be used in its current form in high humidity loads – e.g. using a product without the paper layer on the "cold" side to rise the critical RH criterion or applying additional moisture retarder could be considered. Furthermore, possible problems caused by moisture diffusion flux toward the interior will have to be evaluated.

IQ-T behaved similarly to PIR, however the thicknesses differed. Thus the materials could not be compared directly and the effect of its capillary active channels will need further assessment.

AAC and CaSi exhibited almost equal absolute humidity behind the insulation, with the difference in RH due to lower thermal transmittance of the AAC layer. To reduce the RH levels, lower thicknesses of insulation (in both AAC and IQ-T cases) should also be evaluated.

The temperature on the inner surface was increased compared to the existing wall and thermal transmittance was halved almost in all the cases.

Based on the measurement results the simulation models for the further computational analysis of different brick wall constructions and climate conditions were calibrated.

6 ACKNOWLEDGEMENT

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