Hygrothermal assessment of internally insulated brick wall based on numerical simulation

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Abstract. Massive walls exposed to external climate are characterized by low levels of thermal insulation. Unfortunately in many cases, due to the historic character of the building, the only possible way to improve their thermal insulation is the use of internal insulation. However, such solutions are associated with the risk of frost damage, mould growth or interstitial condensation. Calculations regarding the occurrence of these risks require complex calculation methods. Therefore, in the present work, the evaluation of the hygrothermal behavior of the internally insulated solid brick wall was performed based on the numerical simulations using the program WUFI Pro. Various material solutions of internal insulations, based on both synthetic and natural materials, were compared. The focus was on a particularly sensitive interface between the insulation and the original wall.

1. Introduction

The improvement of thermal insulation for external partitions is an important and effective means to achieve energy savings in relation to existing buildings [10]. The process of building’s retrofit is complex and require integrating different aspects, which should be taken into account, i.a: the interaction between the building envelope and its internal environment to balance energy costs, feasibility, ecology, aesthetics and user comfort [1]. In the case of heritage buildings, and all other where there is no possibility of interference in the appearance of external façade, the only possible solution becomes the use of interior insulation. However, the improper interior insulation thermal modernization of the walls can lead to undesirable thermal bridges, interstitial condensation, and frost damage in outer layer. Therefore, all issues related to the presence of moisture in a partition should be considered at the design stage.

Among the interior insulation systems, there are both vapour-tight and vapour permeable solutions [5]. The former type includes the diffusion-tight, synthetic foams, which impede the vapour diffusion from the indoor space. In the case of this type of insulation it is necessary to lay it very carefully, ensuring a perfect tightness, and avoiding an uncontrolled flow of vapour through the partition. Such solutions limit the drying potential, leading to increased moisture content in the underlying wall [7]. On the other turn, the vapour-permeable solutions allow the exchange of water vapour between the masonry and the indoor environment. However, it may lead to interstitial condensation, especially during the heating season, when the warm vapour is penetrating from the indoor to the cold masonry through the insulation layer [8]. Therefore, in order to avoid the excessive moisture accumulation in the masonry, as an alternative solution, the capillary-active systems are
promoted, allowing moisture to dry out towards the indoor space [2, 6]. However, the question is, what their performance will be when they are exposed to uncontrolled indoor climate conditions.

The hygrothermal simulation software WUFI Pro was used to evaluate the moisture performance of traditional masonry wall with internally added thermal insulation with both synthetic and natural materials such as: cellulose, aerogel, phenolic foam, calcium silicate. As an indicator for the assessment, the relative humidity level at the interface between the insulation and masonry was used. The presented analyses related only to a typical one-dimensional cross-section, and did not take into account structural details such as corners, joints of floor beams, etc., simplifying the masonry wall to the homogenous layer. According to Vereecken and Roels [9], such approach is allowed for assessing the hygric behaviour of masonry wall, provided that the analyses are made in relation to real climatic data.

2. Materials and methods
As a case study, a traditionally constructed masonry brick wall, insulated internally was used. In its original form without any insulation, the wall was referred as a base wall. The base wall, named “historical” has an overall thickness of 380 mm and internal lime plaster. For testing the wall’s hygrothermal performance the WUFI Pro 5.3 [12] software tool, based on numerical simulation in accordance with EN 15026:2007 [3] was used. The analyses were done for four different insulation product, characterized in the table 1.

| Table 1. Comparison of the insulation products assessed in the case study. |
|-------------------------------------------------------------|

| Product name | Cellulose fibres, sprayed | Aerogel blankets | Phenolic foam boards | Calcium silicate boards |
|---------------|---------------------------|------------------|----------------------|------------------------|
| Description   | sprayed cellulose fibres, finished with plaster-board | aerogel-coated polyester mesh, bonded to plasterboard | boards made from phenolic resin, foil and plaster-board | calcium silicate boards, finished with lime plaster |
| Natural or synthetic | natural (plant fibres) | synthetic (aerogel & polyester) | synthetic (phenolic resin) | natural (sand &lime) |
| λ value ranges [W/(m·K)] | 0.035-0.046 | 0.013-0.014 | 0.020-0.025 | 0.045-0.065 |
| Vapour resistance | air | air | air | air |
| Absorption behaviour | highly permeable | permeable | impermeable | hygroscopic |
| Capillary behaviour | hygroscopic | hydrophobic | not hygroscopic | hygroscopic |
| Capillary behaviour | capillary active | capillary inactive | capillary inactive | highly capillary |
| AVCL4 incorporated in product | no | no | yes | no |
| Fixing method | bonded to masonry (no separate adhesive) | mechanically fixed to battens | mechanically fixed to battens | bonded to masonry with adhesive |
| Air gap at insulation | no | yes | yes | no |

4 AVCL-air and vapour control layer.

Depending on the insulation product, the materials include insulation, plasters, plasterboards, adhesives, vapour barrier and air cavities. The material properties used in the case study are listed in table 2 and 3, respectively with data provenance.
Liquid transport
(100% Free water saturation resistance factor [-])
Vapour diffusion [W/(m²K)]
Thermal conductivity [W/(m·K)]
Specific heat capacity [J/(kg·K)]
Porosity [m³/m³]
Bulk density [kg/m³]

- manufacturer’s data
- WUFI data
-N – EN ISO10456:2009 [4]

The chosen insulation products were compared for different target U-values: U=0.23 W/(m²·K), U=0.2 W/(m²·K), regardless of typical thicknesses with which they are supplied to the market. Installing an air and vapour control layer (AVCL) between plasterboard and insulation is often considered as a good practice, therefore assessment undertaken with and without AVCL was made.

Boundary conditions were chosen as follows: The investigated wall was assumed to face North-West direction. The building was modelled as a high building, and the wall was vertical. Driving rain water absorption was set to 70%. Weather data, including hourly values for Warsaw, according to WUFI, were used. The indoor moisture and temperature conditions was taken as normal according to

Table 2. Properties of insulation and brick

| Material properties                  | Cellulose fibres, sprayed | Aerogel blankets | Phenolic foam boards | Calcium Silicate boards | Historical brick | Vienna brick |
|-------------------------------------|---------------------------|------------------|----------------------|-------------------------|-----------------|--------------|
| Bulk density [kg/m³]                | 55 W                      | 146 W            | 43 N                 | 222 P                   | 1800 W          | 1560 W       |
| Porosity [m³/m³]                    | 0.93 P                    | 0.92 W           | 0.95 W               | 0.92 P                  | 0.31 W          | 0.38 W       |
| Specific heat capacity [J/(kg·K)]   | 2544 P                    | 1000 W           | 1400 N               | 1303 P                  | 850 W           | 850 W        |
| Thermal conductivity [W/(m·K)]      | 0.036 P                   | 0.014 W          | 0.023 N              | 0.057 P                 | 0.6 W           | 0.6 W        |
| Vapour diffusion resistance factor [-] | 2.0 P                    | 4.7 W           | 50 N                 | 5.4 P                   | 15 W            | 15 W         |
| Free water saturation (100%-RH) [kg/m³] | 494 W                    | 213 W             | 0 W                  | 815 P                   | 230 W           | 368 W        |
| Liquid transport coefficient [m³/s] | 2.3x10⁻⁷ W                | 1.3x10⁻¹¹ W      | 0 W                  | 4.9x10⁶ P               | 5.0x10⁻⁴ W      | 1.5x10⁻⁵ W   |

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Table 3. Properties of materials used in the case study.

| Material properties                  | PE membrane | Intello membrane | PCV foil | Lime plaster | Air cavity | Adhesive | Gypsum plasterboard |
|-------------------------------------|-------------|------------------|----------|--------------|------------|----------|---------------------|
| Bulk density [kg/m³]                | 130 W       | 115 W            | 130 W    | 1600 W       | 1.3 W     | 1410 P              | 700 N               |
| Porosity [m³/m³]                    | 0.001 W     | 0.086 W          | 0.001 W  | 0.3 W        | 0.999 W   | 0.468 P              | 0.65 W               |
| Specific heat capacity [J/(kg·K)]   | 2200 W      | 2500 W           | 2300 W   | 850 W        | 1000 W    | 1059 P              | 1000 N               |
| Thermal conductivity [W/(m·K)]      | 1.65 W      | 2.4 W            | 2.3 W    | 0.7 W        | 0.155 W   | 0.06 P              | 0.21 N               |
| Vapour diffusion resistance factor [-] | 87 000 W    | 26 000 W         | 20 000 W | 7 W          | 0.51 W    | 22.9 P              | 8.3 N                |
| Free water saturation (100% RH) [kg/m³] | 0 W         | 85 W             | 0 W      | 250 W        | 0 W       | 280 P               | 400 W                |
| Liquid transport coefficient [m³/s] | 0 W         | 0 W              | 0 W      | 1.5 x 10⁻⁷ W | 0 W       | 7x 10⁻¹⁰ P         | 4.5 x 10⁻⁷ W         |

- WUFI data
-N – EN ISO10456:2009 [4]
-P – manufacturer’s data
EN 15026:2007 [8]. The initial temperature in the existing wall was constant and equal to 20°C. The initial moisture content profile was the final profile in the base wall after equilibrium was reached. The simulation started on the first day of October so as to take into account the whole heating season and was carried out for the period of ten years, assuming that it is the adequate length for solid wall to reach equilibrium.

As high relative humidity levels can lead both to mould growth and moisture related damage, the relative humidity at the interface between insulation and masonry wall were investigated. To assess the conditions for the mould growth and frost risk, according to WTA guideline [11], the critical level RH>95% for fully bonding systems and RH>80% for the other solutions was adopted.

3. Results

3.1. Influence of internal insulation product

Figure 1 shows the changes of relative humidity over time, at the condensation critical location for all analyzed cases.

![Figure 1](image-url)

**Figure 1.** Relative humidity at the interface between insulation systems and base wall (the numbers after the names of materials refer to the target of U-values).
The application of internal insulating layer caused in all cases an increase in the relative humidity at the insulation-masonry interface, due to the lowering the temperature in this cross-section. This increase does not always mean damage. The key to assessing a given solution is the analysis of RH level obtained and the consequences of using this solution.

For the cellulose fibre without AVCL figure 1 shows rapid increase of relative humidity in the initial period, than the humidity fluctuate annually between 92-97% for $U=0.20\ W/(m^2\cdot K)$ and 88-96% for $U=0.23\ W/(m^2\cdot K)$. This initial surge is associated with the immediate temperature drop within the insulated wall. Because the cellulose fibre insulation is highly permeable, this initial moisture content decreases by the water vapour diffusion to the room. The humidity at the insulation masonry interface varies seasonally but there is no an increase in the following years and the moisture is not accumulating at the critical location. The adhered nature of the cellulose fibre insulation without AVCL ensures that the probability of air gaps and air paths is negligible so this solution according to WTA key criterion (95% RH threshold) could be acceptable.

The graphs in figure 1, for cellulose fibre with AVCL shows that the use of AVCL changes the performance considerably. After using the Intello membrane, the relative humidity increased to 97.5% and applying PE foil up to 99.2%. With regard to 95% threshold, the retrofits with AVCL exceed this threshold for the whole analyzed period, so this solutions have the potential to cause moisture damage. We can see that the variable character of diffusion for Intello membrane with masonry wall is less advantageous than in lightweight construction because the reverse diffusion effect is much weaker.

Figure 1 for aerogel blanket retrofits, shows that the oscillation fluctuation in relative humidity is very similar to that of cellulose fibre without AVCL, both material have the similar vapour permeable. But the 80% threshold is exceeded for both options.

For phenolic foam option, figure 1 shows that the relative humidity increases over the first two years and then reaches equilibrium, with fluctuations caused by the seasonal changes in temperature. In the case of AVCL membrane, the situation is different. In the first years of operation, the high level of relative humidity is maintained due to the increase of moisture in the air gap caused by the high diffusion resistance, additionally increased by the use of PVC foil, limiting the diffusion of water vapour through the insulation back into the room. It would seem that this solution will cause an increase in moisture content over time. However, after the period of increasing, the relative humidity reaches a state of dynamic equilibrium.

For calcium silicate boards, as Figure 1 shows, the relative humidity reaches an equilibrium quickly with annual fluctuation between 94 to 96%. Although the 95% threshold is exceeded only temporarily and the maximum relative humidity is similar to the case of cellulose fibre retrofits, the amplitude of these fluctuation is smaller. The ability of calcium silicate boards to easily transport moisture through capillary action increases the drying potential of the wall and therefore greatly reduces peaks in moisture at the critical location, but the average relative humidity level is higher than in case of cellulose fibre.

### 3.2. Influence of base wall material

It is often extremely difficult to assign the right input data to the material that was actually used in the solution being analyzed. In order to determine what effect the external layer has on the moisture conditions in the wall, the analyses were also performed for wall solutions with special type of brick named "Vienna". “Historical” brick has the higher capillary transport coefficient, i.e. it absorbs water faster, but at the same relative humidity stores less water than “Vienna” brick. In the case of exposure of both bricks to external moisture, e.g. to heavy rain, "historical" brick will be much more susceptible to damage than “Vienna” brick. Table 2 presents the basic thermal and moisture properties of these two materials. The results of the simulations are presented in Figure 2. As previously, the graphs show the relative humidity at the insulation-masonry interface but for “Vienna” brick.
Figure 2. Relative humidity at the interface between insulation systems and base wall, with external surface from “Vienna” brick (the numbers after the names of materials refer to the target of U-values).

We can see that applying the external layer of wall made from the materials with reduced rain water absorption results in lower relative humidity at the insulation-masonry interface. Comparing the corresponding options (figure 1 with figure 2), the biggest differences in relative humidity occurs in the less water vapour permeable retrofit option – phenolic foam board. With “historic” brick, relative humidity exceeds 100% in the initial years and in subsequent years, this value stabilizes but is subject to high seasonal fluctuations. On the other hand, in the case of “Vienna” brick, the initial level of relative humidity is lower than 100% and in the subsequent years shows a downward trend. In addition, the amplitudes of seasonal variations in the case of “Vienna” bricks are also smaller.

For cellulose fibre retrofit without AVCL in turn, the type of the material forming external layer does not have such an important effect on the humidity conditions inside the wall. The range of relative humidity for “historic” brick is 97-88%, while for “Vienna” brick amounts to 92-86%, so these are not significant differences. However, when using AVCL, the differences become more visible i.e. from 99-98% for “historical” bricks to 93-87% for “Vienna” brick. It indicates that the
solution based on cellulose fibre insulation with AVCL, combined with the more absorbent external layer can lead to significant water accumulation at the insulation-masonry interface.

4. Summary and conclusion
In this paper, the hygrothermal influence of different interior materials was investigated by a numerical simulation. It was shown that applying internal insulation has a high impact on the hygrothermal behavior of the wall, leading to a higher moisture level in the masonry wall and a higher risk of frost and mould damage.

The case study has demonstrated that the moisture absorption characteristic of external wall surface determines the importance of the different transport mechanisms. When moisture transport in internally insulated brick wall occurs, AVCLs appear to have a poorer performance than vapour–open or capillary active insulation retrofits. Reducing the absorption characteristic of wall outer surface can get more freedom to choose the insulation product.

Hence, the other important parameter which has a high influence on the magnitude of these hygrothermal changes is the brick type. It was shown that the moisture storage function is insufficient to estimate the hygrothermal impact of interior insulation, more detailed material properties like liquid conductivity coefficient should be known.

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