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INTERNAL INSULATION AS A SOLUTION FOR REFURBISHING HISTORIC BUILDING ENVELOPES: NUMERICAL HYGROTHERMAL ASSESSMENT AND ENERGY CONSUMPTION COMPARISON

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ABSRACT

A numerical simulation is used for hygrothermal assessment of different wall assemblies in a historical urban residential building from the 19th century in Prague after adding 3 different thermal insulation materials; calcium silicate, vacuum insulation panels and mineral wool to the internal surface of the wall. Water content, relative humidity and temperature fields in the insulated wall layers are calculated after applying the three materials using the software WUFI. Temperature and relative humidity fields in the wooden beam-heads which are embedded in pockets in the insulated walls after applying calcium silicate and mineral wool are calculated using 3D Cube. Calcium silicate and mineral wool are applied in a thickness of 10 cm and their influence on the hygrothermal behavior of the wall assembly is tested before and after adding a vapor barrier. For comparison, the influence of mineral wool insulation on the hygrothermal behavior of the wall is tested later for an insulation thickness of 5 cm with a vapor barrier on two wall thicknesses 45 cm and 61 cm. A numerical calculation using Energie 2020 is conducted to compare the influence of the three selected insulation materials on the energy need for heating the historical building compared to the following refurbishment measures; external insulation to the backyard facade, insulating the roof and insulating the floor. Based on the hygrothermal analysis and on the energy consumption calculation of different refurbishment measures, it is recommended during the decision-making process of future energy refurbishments of similar urban residential buildings from the 19th century, to consider refurbishments solutions as external insulation of the backyard facade or insulation of the roof or the floor as preferable options before considering the intervention with internal insulation.

KEYWORDS

Internal insulation, Historical buildings, Hygrothermal behavior, Energy consumption

INTRODUCTION

Since buildings account for around 40% of the total energy consumption [1], there is a big potential for a CO2 reduction through energy efficiency of buildings. Substantial savings in heating energy appears as one of the key factors in the optimization of energy consumption. 69% of the energy consumption in residential buildings in the Czech Republic is used for heating, compared to approximately 66% in the EU [2]. Therefore, large energy savings are expected due to increased thermal resistance of the building envelope. Measurements as additional external insulation to the walls, insulting the roof or the floor appear as the most straightforward way to achieve almost immediate improvements in heating energy, however in some cases the measurement of adding internal insulation is implemented, as in the case of historical buildings which are protected by the authorities. For such buildings any changes to the appearance of the original facade are not tolerable. Adding internal insulation has in several cases led to many problems. The main problems are increased moisture level and condensation. The problem of increased moisture level in the wall could be caused by closing the pores of the wall materials (bricks, lime etc.), which prevents the moisture from drying out, or it could happen if the outer wall becomes too cold and can’t evaporate accumulated moisture. The problem of condensation could appear when the temperature of the interface between the wall and the internal insulation drops below the dew point. Another detail that requires attention after adding internal insulation is the wooden beams placed in pockets embedded in the brick wall. These beams were typically used to support the ceiling structure of historical buildings from the 19th century in Czechia. After adding internal insulation, temperature and relative humidity change in the beam head possibly creating a suitable environment for mold growth. Their organic material is sensitive to moisture damage and biodegradation creating a risk of wood decay. There are a few more disadvantages of adding interior insulation as in losing inner space, thermal bridges and not seeing the original material from the inside.

Considering all these complications of adding internal insulation to historical brick walls and aiming to make better and more suitable decisions during planning future refurbishments of historical buildings, this paper numerically simulates the hygrothermal behavior of the wall structure after adding 3 variants of internal insulations; calcium silicate, vacuum insulation panels and mineral wool. Calcium silicate and mineral wool are applied in 10 cm thickness without and later with a vapor barrier. Mineral wool is applied again in 5 cm thickness with a vapor barrier on a 45 cm and later on a 61 cm thick wall. Added to that, this study numerically simulates the relative humidity and temperature fields in the wooden beams embedded in the insulated walls with calcium silicate and mineral wool in 10 cm thickness. The simulation is repeated after insulating with 5 cm mineral wool with a vapor barrier. for comparison reasons, the energy needed for heating the building after each measurement; internal insulation using the mentioned three materials, insulating the roof, insulating the floor and insulating the backyard façade are numerically calculated. An existing historical building from the 19th century has been chosen to be the study object. This building stands in Prague, Czechia and is protected by the authorities for its cultural value.

METHODS

A residential historical building that is in the historical protected zone in Prague, Czechia, is chosen for the purpose of this study. This object was built in the year 1888. The appearance of its historical façade is considered valuable for its urban value, therefore changes to it are strictly prohibited. The structure of this object shares similar characteristics with residential buildings in Czechia dating back to the 19th century. The exterior walls are built of solid bricks, rendered with a standard traditional lime plaster on both sides. The ceilings are supported by wooden beams embedded in pockets and resting in the brick walls. The exterior walls are 69 cm thick on the ground floor, with a decrease of 8 cm in each floor. This paper studies the hygrothermal performances of the walls after insulating the 45 cm and later the 61 cm thick walls.

The historical, protected façade is directed to the south. while the backyard facade is oriented toward the north. The east and west sides of the building envelope are shared with the neighbouring buildings. A big reconstruction in 2000 altered the building envelope. This paper works with the original state of the object, relying on personal visits to detail the initial building envelope and on the historical documentation of the building provided by the owner. The floor plan and section are presented in Figure 1 and Figure 2 where the information about the layers of the historical structures, dimensions, areas, and volumes used in the simulations are collectable.

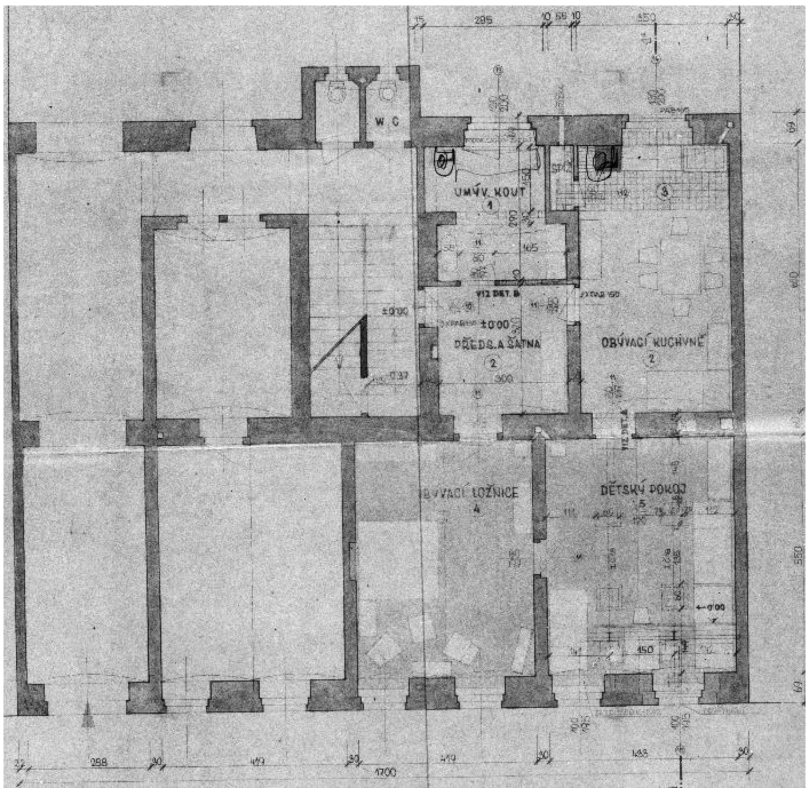

Fig. 1 – floor plan of the studied object used in the simulations.

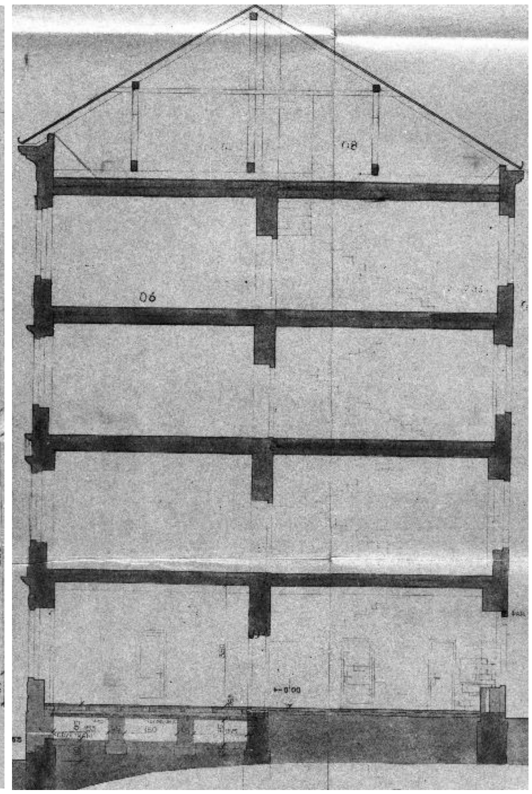

Fig. 2 – section in the studied object.

The hygrothermal performance of the wall after internally adding 3 different insulations is numerically tested using the software WUFI for a study period of 6 years. Internal insulation thickness of 10 cm is the largest suggested to be used in this object, first to limit the light and sun blockage caused by increasing the internal thickness of the wall around the windows and second to limit the loss in internal space area. Thickness of 5 cm is used to compare how decreasing the thickness of the insulation to half can affect the hygrothermal behavior of the wall. As mentioned earlier, the hygrothermal performance simulation was repeated after adding vapor barrier layer to the walls insulated with calcium silicate and mineral wool for comparison. Although positioning the vapor barrier closer to the warm internal surface of the wall, for example right under the internal plaster is widely used, this positioning works well only theoretically. In reality, it is very hard to avoid mechanical damage to the barrier as a single nail or hook driven into the wall can largely negatively affect its function. This positioning additionally can limit water vapor removal from internal spaces through the envelope which can lead to increased relative humidity in the interior and worsening of internal air quality.

Weather data of Prague are used for the exterior considering the wind-driven rain. The chosen temperature and humidity level of the interior air simulate the conditions in one of the flats where the measured internal temperatures during winter are between 23º and 25º and relative humidity between 55% and 65%. Since the average measured temperature of 24º and the average relative humidity of 60% are the highest in this flat compared to the measured ones in all other visited flats in the studied building, these conditions are considered as the worst-case scenario which is simulated in this study. The second step of the study is a 3-dimensional numerical test using the software 3D Cube to determine the temperature and humidity level in the wood beams heads. This simulation excludes the influence of rain. It is important to note that this test isn't run for a period of time but only in one climatic state, when the external temperature and relative humidity are -13º, 80% and the internal temperature and relative humidity are 24º ,60%.

The influence of the refurbishment of adding internal insulation on decreasing the energy need for heating the building is compared with the influence of other refurbishments as insulating the backyard façade with 10 cm of mineral wool, insulating the roof with 25 cm of mineral wool or the floor with 15 cm of mineral wool. For this comparison a numerical calculation using the software Energie 2020 is conducted.

MATERIALS

The assembly of the exterior walls of historical objects, solid bricks with lime mortars, is considered as a "breathable" wall assembly. These materials are porous and allow easy water vapor diffusion and moisture transport by the capillary action. The first material chosen for the study, calcium silicate, CaSi (I1), is a capillary active material that facilitates the drying of the wall moisture and is compatible with the original wall materials. This material has been commonly used recently in refurbishments of historical brick walls. The hygrothermal performance of internally insulated brick walls after adding calcium silicate is tested in [3] numerically and in-situ. All the insulation systems presented in [3] are capillary-active where calcium silicate is used. The presented results prove advantageous for the drying process of potential built-in moisture as well as for the limitation of the condensation amount during winter when using these insulation systems. In this paper, calcium silicate is applied on the studied historical brick wall in 10 cm thickness, and later in 10 cm thickness with a vapor-barrier. Although it is not usual to apply I1 with vapor barrier, it is tested here for comparison.

One of the challenges of adding interior insulation to existing walls is that the additional thickness of the wall is limited by the reduction of the internal floor area. New highly efficient thermal insulation materials such as vacuum insulation panels, (I2), increase the thermal resistance of the wall compared to conventional insulation materials with the same thickness. The thermal resistance of a vacuum insulation panel (VIP) is 5-10 times higher than for conventional insulation materials [4,5]. The thickness range of panels is generally 1-5 cm. The panels consist of gas-tight enclosure surrounding a rigid core, from which the air has been evacuated. Panel size ranges between 10 x 10 cm to 125 x 300 cm [6]. The material, if applied perfectly, prevents moisture from traveling from the interior to the construction working also as a vapor barrier. To protect the insulation from accidental piercings, gypsum boards 1,25 cm thick were used.

The third material tested in this article is mineral wool (I3). This material is widely used and available in the market. It is also relatively easy to execute and not expensive, which makes it one of the most attainable options for owners of such historical buildings. In [7] the hygrothermal performance of interior insulation system on the basis of hydrophilic mineral wool applied on a historical brick wall is studied using a semi-scale measuring technology referenced in [8]. In [7], the interior thermal insulation system is applied on 45 cm thick brick wall. The hydrophilic mineral wool boards, 8 cm thick, are fixed on the brick wall using B2 water vapor retarder. The interior and exterior climatic conditions are used to simulate residential buildings in Prague, Czechia. The test results in [7] exhibit a very positive effect of the insulation system on the hygrothermal behavior of the wall even in the most critical part of the year from the point of view of water condensation. Also, the water vapor retarder presented a good capability to control water vapor transport from the interior to the exterior. In this paper, the mineral wool, 10 cm thick, is fixed on the brick wall. Later, I3 is applied in 10 cm thickness with a vapor-barrier. The test is repeated when mineral wool is applied in 5 cm thickness with a vapor-barrier to the 45 cm and later to 61 cm thick wall.

RESULTS

Relative humidity, water content and temperature in the layers of the original and the insulated wall assemblies are numerically calculated using WUFI after internally insulating with I1, I2, I3. Results are presented in Figures 3, 4, 5 and 6.

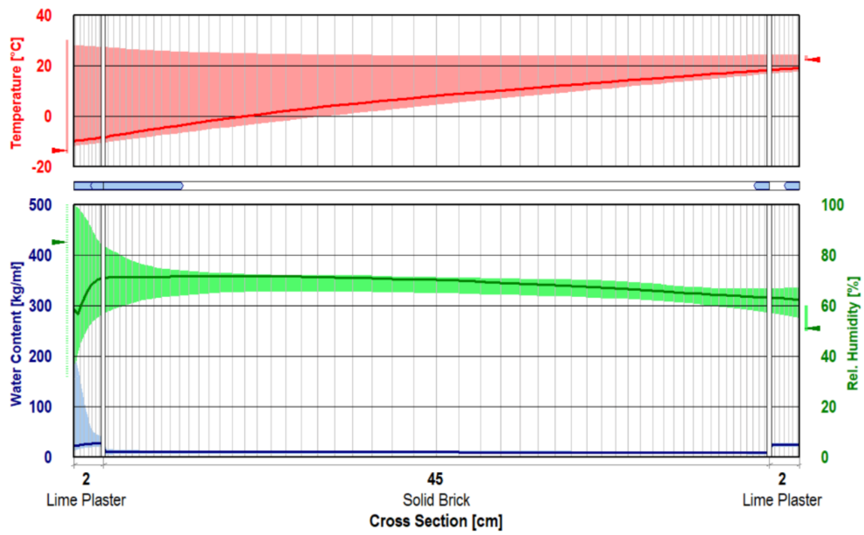

Fig. 3 – __Temperature; __ relative humidity; __ water content of the assembly of the studied wall (brick 45 cm) without insulation.

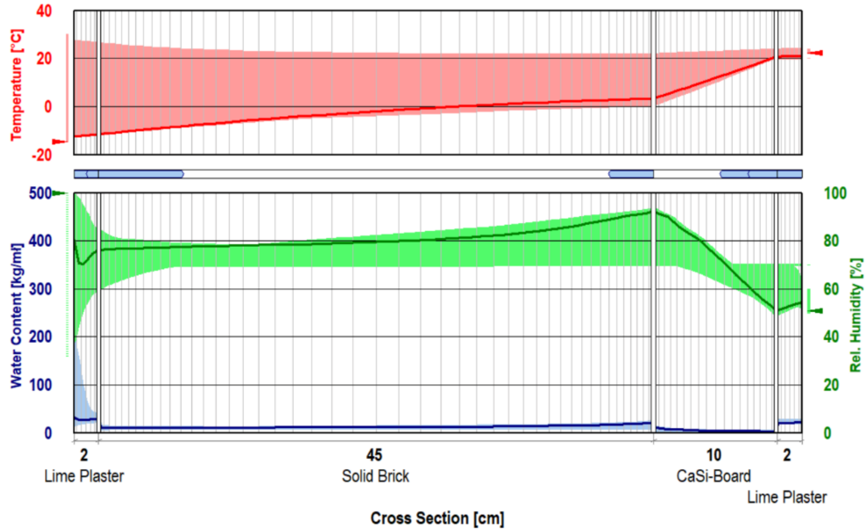

Fig. 4 – __Temperature; __ relative humidity; __ water content of the assembly of the studied wall (brick 45 cm) internally insulated with I1 (10 cm).

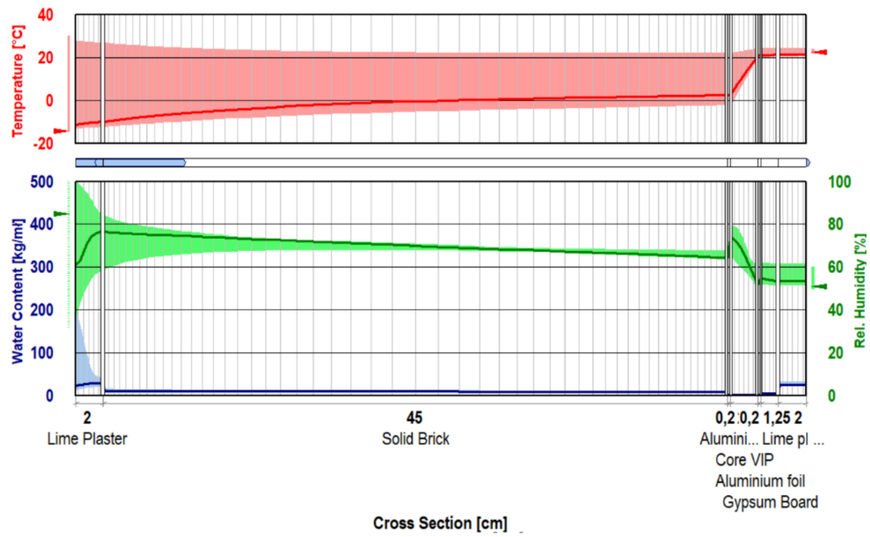

Fig. 5 – __Temperature; __ relative humidity; __ water content of the assembly of the studied wall (brick 45 cm) internally insulated with I2 (2.5 cm).

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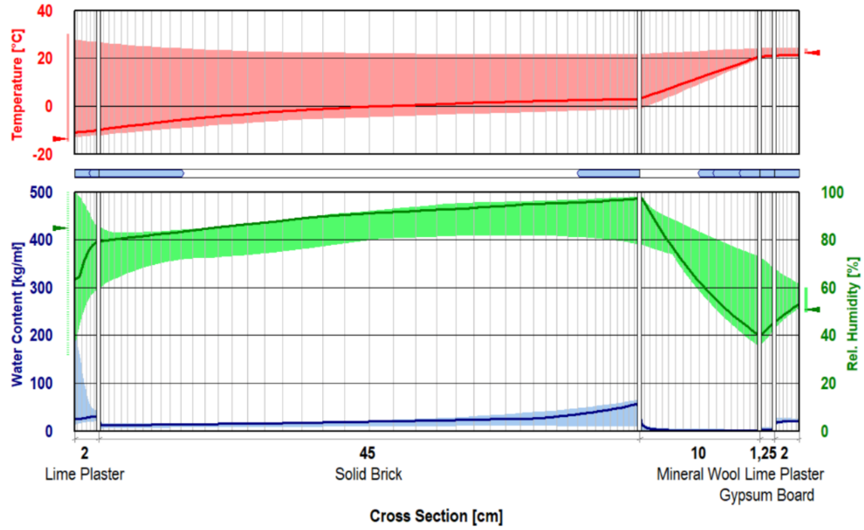

Fig. 6 – __Temperature; __ relative humidity; __ water content of the assembly of the studied wall (brick 45 cm) internally insulated with I3 (10 cm).

A big influence on the relative humidity at the interface between the wall and the insulation is apparent after using the internal insulation materials I1, I3 where it exceeds 90% in winter. More results are reported in Table 1. The total water content in the wall after using I1 and I2 ranges between 5 kg/m^3 and 8 kg/m^3. The total water content in the assembly after using I3 increases every year without a chance to dry all the water it has gained during winter season. For comparison, the temperature, water content and relative humidity in the same wall assembly using insulations I1 and I3, 10 cm with a vapor barrier are calculated with WUFI using the same internal and external weather conditions mentioned earlier. Results are presented in Figures 7 and 8.

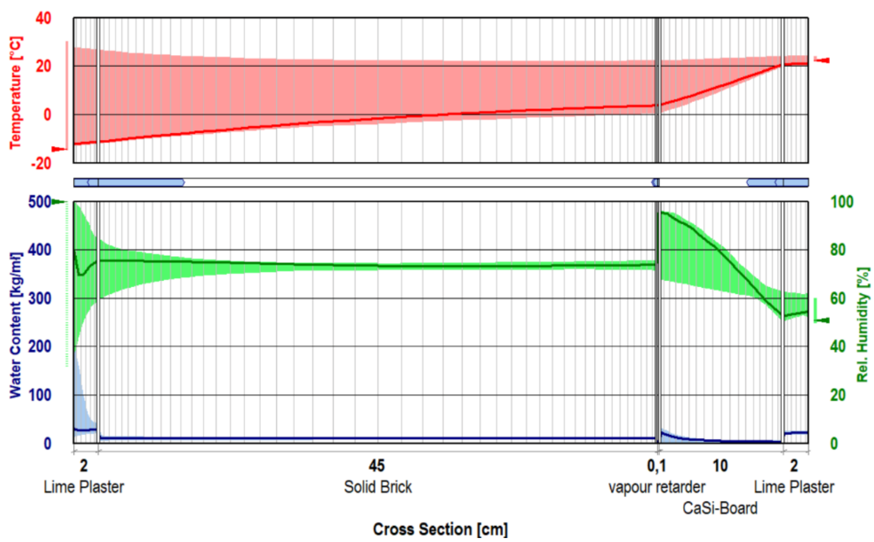

Fig. 7 – __Temperature; __ relative humidity; __ water content of the assembly of the studied wall (brick 45 cm) internally insulated with I1 (10 cm) + vapor-barrier.

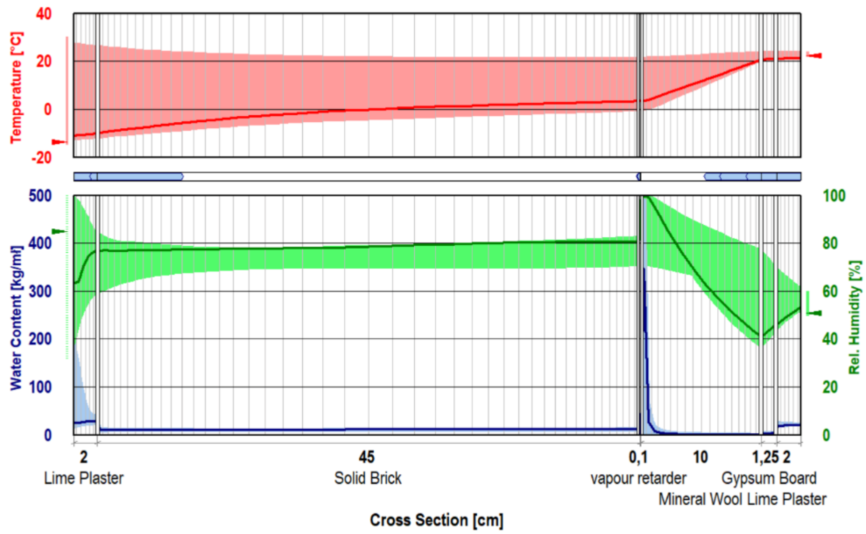

Fig. 8 – __Temperature; __ relative humidity; __ water content of the assembly of the studied wall (brick 45 cm) internally insulated with I3 (10 cm) + vapor-barrier.

The vapor barrier limits the diffusing and condensing water vapor from reaching the brick wall, while the relative humidity in the insulation layer itself exceeds 90% in both materials. The total water content in the wall insulated with I1 ranges between 5.5 kg/m^3 and 7 kg/m^3 while in the case of I3 it starts with 6 kg/m^3 and keeps increasing in every studied year. The numerical calculations for the brick wall, 45 cm thick, are repeated in the same weather conditions after decreasing the thickness of the insulation I3, to 5 cm, with a vapor barrier (Figure 9). Results are also reported in Table 1.

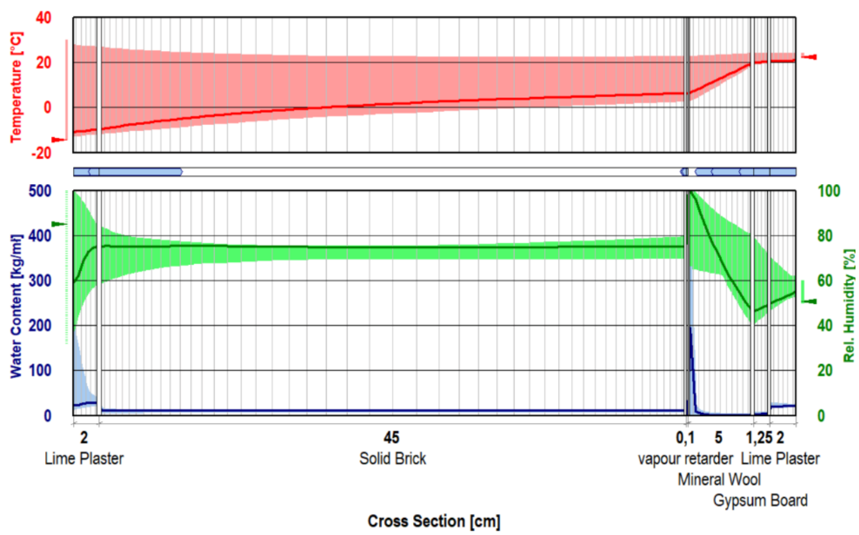

Fig. 9 – __Temperature; __ relative humidity; __ water content of the assembly of the studied wall (brick 45 cm) internally insulated with I3 thickness (5 cm) + vapor-barrier.

Decreasing the thickness of the insulation to 5 cm didn't substantially change the results obtained when it was 10 cm. The relative humidity in the insulation layer still exceeds 90% in winter, while the total water content increases in every studied year. The numerical simulation of the temperature, water content and the relative humidity in the wall assembly is repeated after changing the thickness of the brick wall to 61 cm using insulation I3 in a thickness of 5 cm with a vapor barrier (Figure 10). The results of the test are reported in Table 1.

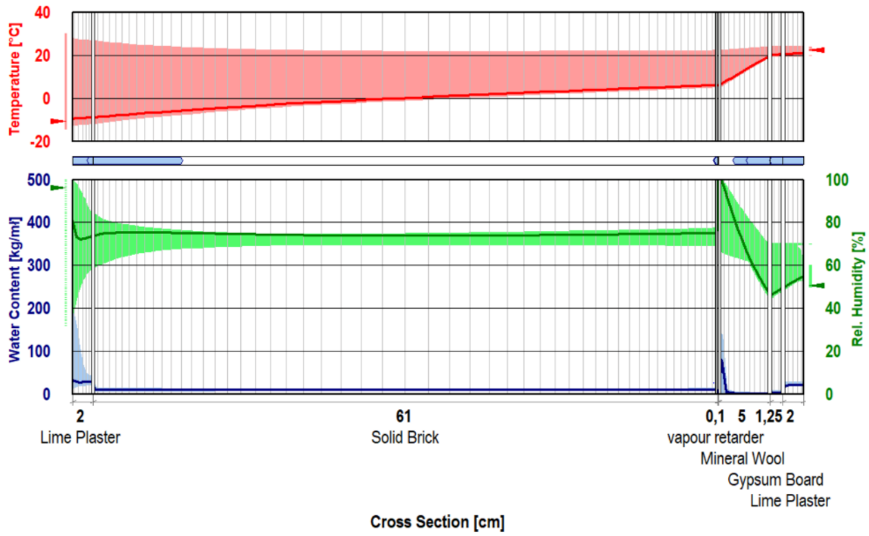

Fig. 10 – __Temperature; __ relative humidity; __ water content of assembly of the studied wall (brick 61 cm) internally insulated with I3 thickness (5 cm) + vapor-barrier.

Tab. 1 - Influence of the used insulations materials on the hygrothermal behavior of insulated wall in the studied period

Internal Insulation	Thickness of the brick layer (cm)	Water content in the insulation (kg/m^3)	Total water content (kg/m^3)
Without insulation	45	-	Min. 4.5 – max. 6 during the studied period of 6 years
I1 (10 cm)	45	3.5-5.3	Min. 6 – max. 8 during the studied period of 6 years
I1 (10 cm) + vapor barrier	45	3.6-8	Min. 5.5 – max. 7 during the studied period of 6 years
I2	45	0,00	Min. 5 – max. 6.5 during the studied period of 6 years
I3 (10 cm)	45	0.8-2.8	Minimum is 6 and it continues to increase in every studied year
I3 (10 cm) + vapor barrier	45	0.9-33.4	Minimum is 5 and it continues to increase in every studied year
I3 (5 cm) + vapor barrier	45	1-34.7	Minimum is 5 and it continues to increase in every studied year
I3 (5 cm) + vapor barrier	61	1-15.6	Minimum is 7 and it continues to increase in every studied year

As visible in the above presented figures, the relative humidity in the insulation layers I1 and I3 after adding vapor barrier exceeds 90% in winter in all the studied cases while it reaches 100% after applying I3 with vapor barrier. This high relative humidity in I3 was not substantially affected by changing the thickness of the brick layer from 45 cm to 61 cm nor by decreasing the thickness of the insulation layer from 10 cm to 5 cm. The thermal properties of the insulation can be greatly negatively affected by the increased water content in the material. In the case of insulating with I1, the insulation dries inwards during the summer, and the total water content of the assembly changes in a stable range in every studied year in both tests before and after adding a vapor barrier. While in the case of I3 the total water content steadily increases in every studied year without a chance to fully dry, in both cases before and after using a vapor barrier.

To test the influence of the used insulation materials on the relative humidity and temperature in the wooden beam heads that are embedded in the insulated wall, a 3D model of part of the ceiling including the wooden beam and part of the brick wall in a thickness of 45 cm was created using the software 3D Cube (Figure 11). Sections showing the relative humidity and temperature ranges in the wood beam and in the pockets where they rest are then presented. The section in Figure 12 shows the relative humidity and temperature in this detail before adding any insulation. The sections in Figures 13 and 14 show the result of the numerical simulation after insulating the wall with 10 cm of I1 and I3. The simulation was repeated after using 10 cm of I3 with a vapor barrier (Figure 15), and then after decreasing the thickness of the insulation I3 to 5 cm with a vapor barrier (Figure 16).

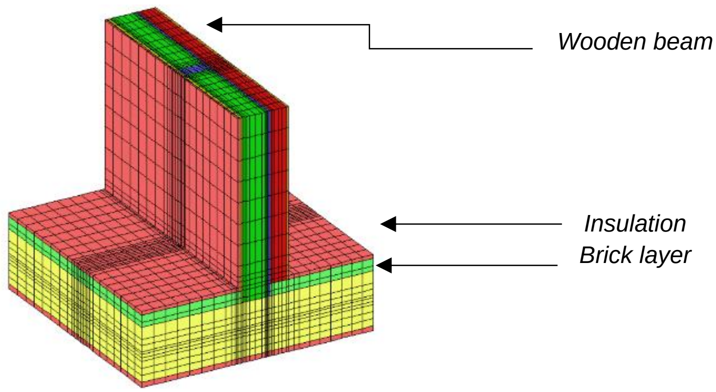

Fig. 11 – A 3D model using 3D Cube of part of the ceiling which includes a wood beam and part of the wall where the beam is embedded.

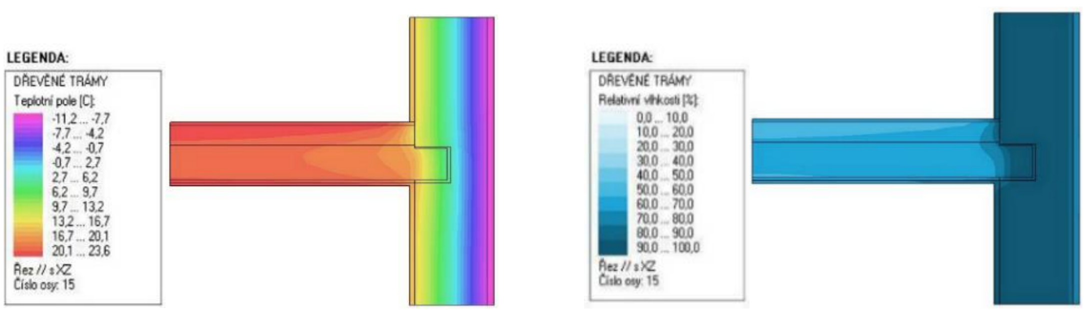

Fig. 12 – Temperature and relative humidity fields in the wood beam embedded in the historical wall without any modification.

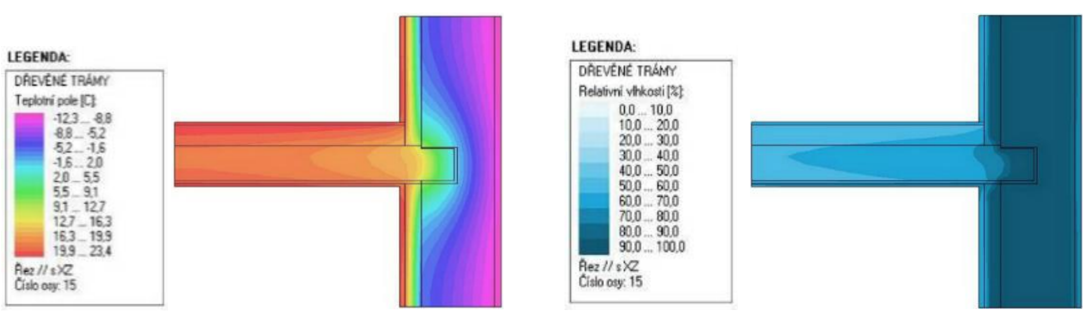

Fig. 13 – Temperature and relative humidity fields in the wood beam embedded in the wall insulated with I1 (10 cm).

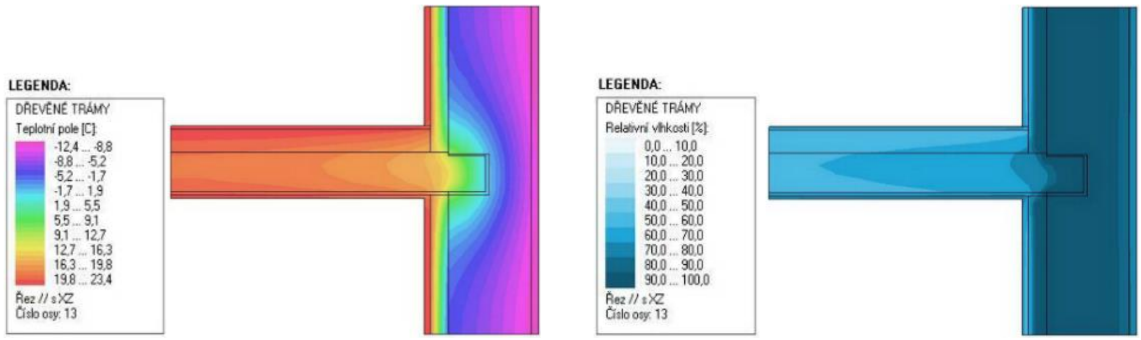

Fig. 14 – Temperature and relative humidity fields in the wood beam embedded in the wall insulated with I3 (10 cm).

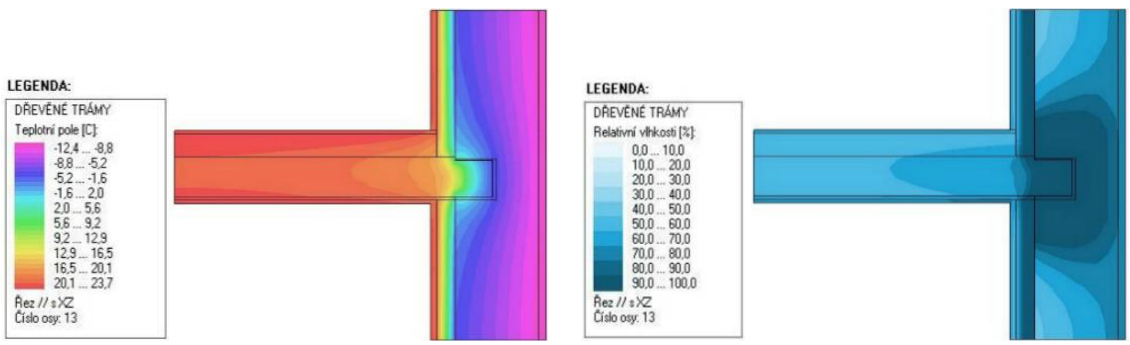

Fig. 15 – Temperature and relative humidity fields in the wood beam embedded in the wall insulated with I3 (10 cm) + vapor-barrier.

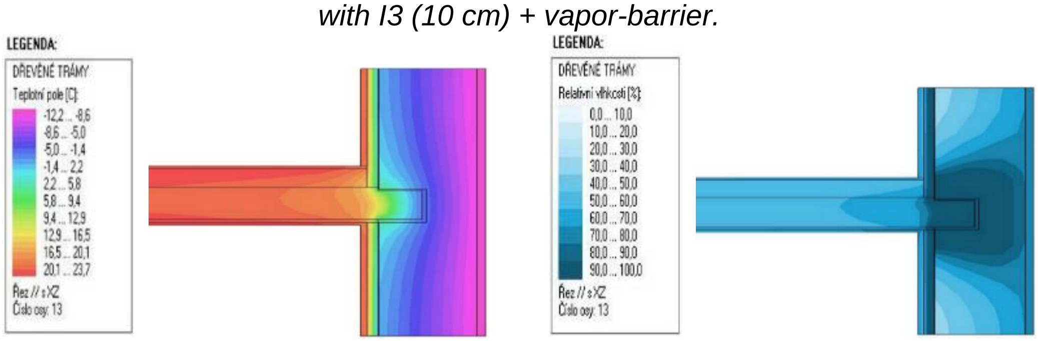

Fig. 16 – Temperature and relative humidity fields in the wood beam embedded in the wall insulated with I3 (5 cm) + vapor-barrier.

The relative humidity in the wood beam head is above 80% in the studied conditions before and after all tested modifications, although, as expected, the temperature after adding insulation decreases. The temperature field in the wood beam-head after insulating the wall with 10 cm calcium silicates (I1) or 10 cm mineral wool (I3) is between -1º and 12º, while after adding a vapor barrier to I3 the temperature field in the beam head is between -5º and 13º. This change in temperature field can be explained by the increased water content in the insulation layer, as it was resulted in the previous measurement and presented in Table 1. This increase in water content affects the properties of the insulation material, therefore changing the temperature field in the assembly. Adding a vapor-barrier to the assembly insulated with I3 results in a decrease in the humidity inside the wall while at the warm surface of the wall and in the insulation layer the humidity level exceeds 80%. Adding a vapor-barrier or changing the thickness of the insulation doesn't result in substantial improvements in the relative humidity level in the wood beam-head that still exceeds 80% while the temperature is above 0º creating suitable conditions for mold growth. In the studies [9] and [10] a slight increase in relative humidity at the wood beam head after using a vapor-tight insulation was noticed when compared with vapor-open insulation.

To improve the decision-making process during future energy refurbishments of similar historical objects, the energy need for heating the building before any modification and after refurbishments of thermal insulation with the three selected materials in the study, external insulation to the backyard façade, insulation to the roof or the floor of the ground floor of the same building were compared using numerical calculation conducted by the software Energie 2020. Results are reported in Table 2. It is important to note that this calculation represents the energy needed to heat the building and not the energy the heating system requires for heating the building. The latter includes the energy needed to heat the building + the energy needed to generate and distribute the heat + energy losses. While the efficiency rate and the losses of energy during generating and distributing the heat vary from one system to the other, the energy need for heating the building stays the same. The mean thermal transmittance of the building fabric of the original building before modifying the envelope is U,em: 1,07 W/(m^2K) and the energy need for heating the building is 149.5 MWh/year.

Tab. 2 - Influence of different measurements on the energy need for heating the building.

Measurement	mean thermal transmittance of the building fabric W/(m^2K))	Energy need for heating the building (MWh/year)
Internal insulation I1 (10 cm CaSi)	1,01	143,6
Internal insulation I2 (2.5 cm VIP)	1,00	142,6
Internal insulation I3 (10 cm mineral wool)	1,00	142,6
Exterior insulation - backyard façade (10 cm mineral wool)	0,97	134,7
Insulating the roof (25 cm mineral wool)	1,02	118,8
Insulating the floor of the ground floor (15 cm mineral wool)	1,00	142,6

All used internal insulation materials show less energy savings compared to the refurbishment measures of exterior insulation to the backyard façade or insulating the roof which results in the lowest energy consumption. The advantages of external insulation of the backyard façade include minimizing thermal bridges, protecting the historical structure from weather conditions and not affecting the internal floor area, while the biggest advantage in the case of historical buildings is not affecting the cultural value. Insulation I2 is complex during execution and maintenance due to its sensitivity to damage, and since the panels have fixed dimensions and cannot be cut. A single nail in the wall or accidental damage can largely change the hygrothermal performance of the assembly and largely affect its insulating properties. Additional complexity during execution of I2 is especially in this type of historical buildings where exterior walls typically do not have a regular thickness throughout their section, but in most cases, it changes below the windows behind the heating equipment. While insulating the floor of the ground floor has a similar influence on the energy needed for heating as the studied thermal insulations, it doesn't introduce the complications that are usually associated with the internal insulation.

CONCLUSION

The hygrothermal behavior of the wall structure after adding 3 variants of internal insulations; calcium silicate, vacuum insulation panels and mineral wool were numerically simulated in this paper. Vapor-open and vapor-tight insulation systems were investigated. Additionally, the influence of adding mineral wool and CaSi on the temperature and relative humidity fields in the wooden beam heads that are embedded in the insulated walls was numerically simulated. Finally, the influence of different measurements on the energy need for heating the building was numerically calculated and compared with the influence of the used internal insulations on the energy need for heating. While the relative humidity in calcium silicate (I1) has exceeded 90% in winter in all tested variations affecting its thermal insulation properties when they are the most needed, the relative humidity in the insulation after insulting with mineral wool (I3) has reached 100% with an increasing total water content in the wall assembly in every studied year. Although vacuum insulation panels (I2) have the advantage of saving internal space and show a stable total water content during the studied period with a relative humidity at the warm side of the brick layer less than 70%, their biggest disadvantages are complication of execution and high sensitivity to damage. It is important to note that the results of this paper are numerically conducted while in reality and due to execution and maintenance challenges, especially of sensitive materials, the results may differ. The hygrothermal performance of the assembly after insulating with I3 with vapor barrier wasn't substantially improved after decreasing the thickness of the insulation from 10 cm to 5 cm, nor after increasing the wall thickness from 45 cm to 61 cm. Simulations of the temperature and relative humidity fields in the wooden beam heads show relative humidity level that exceeds 80% while the temperature is above 0^{o} creating suitable conditions for mold growth.

While, as mentioned above, refurbishing with internal insulation in all tested cases led to one type of complication or the other; raised water content in the insulation itself affecting its thermal performance and lifecycle, increasing water content in the assembly without completely drying, the complication of execution and maintenance which its perfection in reality can't be guaranteed or posing the danger of mold growth and degradation of wooden structural elements, other refurbishment measures as external insulation of the backyard façade or insulating the roof do not pose the same dangers on the historical structure while result in larger energy savings than all tested internal insulations in this study. During energy refurbishments of this type of urban historical residential buildings from the 19th century, it is recommended to first consider refurbishments that include protecting the historical structure as well as the appearance of the façade, as insulating the backyard façade, the roof or the floor, before considering internally insulating the façade since they do not only eliminate the dangers of degradation or raised humidity levels but they also showed a lower energy need for heating.

From the point of view of execution, it is easier to choose one system to insulate the building instead of using more than one in the same structure which can cause complications between different systems. Although more research is recommended to test the feasibility of integrating more than one insulation method in historical buildings. It is important to mention the limitations of this study, as mentioned above, the simulation of relative humidity and temperature in the wooden beams is not run for a period of time but only in one climatic state, when the external temperature and relative humidity are -13°, 80% and the internal temperature and relative humidity are 24° ,60% while excluding the effect of rain. It is not clear from this test the potential of drying or the changes in relative humidity and temperature in the wood beam head when the conditions change throughout the year. All the tests done in this study are numerical which has its own limitations of not including factors as changes in the performance of historical materials due to inevitable degradation or possible imperfections during execution or maintenance which are important topics for further research. More research is also recommended to study the long-term impact of different internal insulation systems on the historical structure.

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