Historic Building Simulation of the Internal Insulation Behavior in Climate of Slovakia in a Case Study

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Abstract. Main topic of the article speaks about historic building renovation in Košice. Nowadays, the building is in use as puppet theatre. The theatre suffers from various disorders caused by humidity. The envelope of building has been renovated several times, however, over time, the faults return over and over. The article can be divided into two parts. The first one presents the results of moisture analysis of the support wall. The samples from the facade probes were evaluated by gravimetric method. The second part of the article discusses the interior insulation of a historic building. Internal insulation is one of the solutions to reduce heat loss of historic buildings. The use of this type of insulation brings risks that affect the thermal-humidity behaviour of the perimeter structure. These risks are assessed using a simulation model. In addition to the risks, the impact of the insulation on the original wall structure and the impact on the indoor environment were also assessed. Based on the simulation results, we can assess whether the restoration approach is appropriate in this specific case of using insulation. The study shows that the initial humidity of the perimeter wall structure is an important factor for internal insulation. Before applying the internal insulation, it is necessary to examine the moisture and material properties of the masonry.

1. Introduction
Historic buildings built before 1945 form an important part of the European building stock. Most of these buildings have a high architectural or cultural value, but they also consume almost 40% of the total energy consumption of buildings and are responsible for 36% of CO2 emissions from buildings in Europe. Historic buildings are therefore an important area for focusing on achieving the EU's climate and energy goals. By installing internal insulation on the perimeter walls, it is possible to save potentially 15-20% of the total energy consumption of the building. Insulation increases the insulating properties of the walls and can also improve the level of thermal comfort. According to [1], in order to choose the right insulation solution, it is important to know the thermal-humidity properties of materials in existing structures and in insulation systems. The most important are the thermal conductivity \( \lambda \) W/(m.K), the capillary absorption coefficient \( A_{\text{cap}} \) (kg/(m\(^2\)s\(^{0.5}\))) which is related to capillary activity and also the diffusion resistance factor \( \mu \) (-) [1] [2].

Exterior insulation is the most effective way to reduce heat flux through perimeter structures and is also the safest in terms of the humidity mode of the structure, [3-8]. However, thermal insulation of historic buildings from the outside is inadmissible due to the high cultural value of historic facades and their elements. In order to reduce energy consumption, it is therefore necessary to use a thermal insulator from the inside. However, this approach is accompanied by large number of risks such as interstitial condensation, reduced the drying potential of the structure inwards and after that resulting in increased
moisture in the structure and thus the risk of mould growth [9-14]. Damage to wooden beams due to wood rot can occur when the wooden beam ends are no longer located in the warm part of the wall [15].

On the market are available various types of insulation that are suitable for the internal insulation of historic buildings [16]. These are capillary active and hydrophilic insulations [17], [18] and commonly used hydrophobic insulations with a vapour barrier. Researchers from the Faculty of Civil Engineering of the Technical University in Košice also dealt with the topic of historic buildings in various publications [19-25].

Regarding to the mentioned negative effects of internal insulation on the thermal behaviour of the perimeter structure of a historic building, the aim of the article is to design and optimize the thickness of thermal insulation on the internal surface. The evaluation parameter of the design efficiency is the temperature and humidity profile in the structure. The monitored criterion is the dew point temperature on the inner surface of the masonry under the proposed thermal insulation. An indicator of the reliability of the structure is the long-term simulation of the water content in the structure after insulation. The logical requirement is to maximize the thickness of the thermal insulation to minimize heat loss by transmission through the perimeter wall. However, with increasing thermal insulation thickness, there is a risk of deterioration of the thermal-humidity mode of this structure. By interacting the mentioned requirements with the help of progressive simulation methods with the simultaneous use of laboratory devices, the main goal of the paper is to achieve the maximum functional and optimal design of the internal insulation of the perimeter wall of a historic building.

2. Moisture analysis

2.1. Sampling

The moisture survey of the building was carried out on 19.11.2020 in the time from 8:00 to 10:30, when the destructive method was used to take samples from the plinth part of the perimeter masonry oriented to the north-east (Figure 1). The plaster of the plinth part repeatedly falls off and for this reason most of the probes were concentrated on this part of the perimeter structure. 7 probes were made from which 14 samples were taken. The probes were performed at three height levels of 0.3 m; 0.5m; 1.0 m at depths of 0.001 to 0.10 m (Figure 2,3). Samples were taken with a hammer and chisel as well as a drill.

Figure 1. North-east facade of the puppet theatre
Figure 2. Sampling points of the perimeter facade oriented to the northeast-left plaster sample, right brick sample.

Figure 3. North-east facade of the puppet theatre with marked probes – on the left south part on the right north part of the facade

2.2. Moisture measurements of wall samples
The evaluation of samples was performed in the laboratory of Institute of Architectural Engineering TUKE. Mass moisture content was measured by a gravimetric method using a Sartorius MA 150 moisture analyser (Figure 4). The SARTORIUS MA 150 moisture analyser uses an analytical method to evaluate the weight loss of a wet sample using a built-in dryer, which we call the thermo-gravimetric method. The heating source is a ceramic IR heating element that evenly heats the sample surface. The weighing capacity of the device is 150g with a measuring accuracy of 1mg. The built-in heating element works in the temperature range of 40 - 180 °C [26]. Before the measurement, it is necessary to shred the samples and pour approximately 5g of material. The weight moisture of the samples can also be determined manually using a formula:

$$w_m = \frac{m - m_s}{m_s} \times 100\% hm$$ (1)

Where:

$w_m$ – water content in mass percent (%hm)

$m$ – weight of the wet sample (g)

$m_s$ – weight of the dry sample (g)
2.3. Evaluation of samples
The results of laboratory measurements were compared with standard values for determining the moisture content of the plinth part of the perimeter masonry (Table 1, 2).

**Table 1.** Moisture classification according to STN P 73 06 10

| Moisture    | Moisture content in % by mass |
|-------------|--------------------------------|
| Very low    | < 3                            |
| Low         | 3,0-5,0                        |
| Increased   | 5,0 – 7,5                      |
| High        | 7,5 - 10                       |
| Very high   | > 10                           |

**Table 2.** Results of moisture analysis

| Marking of probes | Description of the samples | Moisture content in % by mass | Moisture classification according to STN P 73 0610 |
|-------------------|----------------------------|-------------------------------|----------------------------------------------|
| 0Bj               | Plaster                    | 3,67                          | Low                                         |
| 1Bv               | Plaster stucco             | 1,8                           | Very low                                    |
| 1Bj               | Plaster                    | 1,27                          | Very low                                    |
| 2A                | Fired brick                | 1,08                          | Very low                                    |
| 2Bj               | Plaster                    | 2,12                          | Very low                                    |
| 3Av               | Fired brick                | 5,29                          | Increased                                   |
| 3Ah               | Fired brick                | 6,14                          | Increased                                   |
| 3Bv               | Plaster stucco             | 1,34                          | Very low                                    |
| 4A                | Fired brick                | 2,56                          | Very low                                    |
| 4Bv               | Plaster stucco             | 3,53                          | Low                                         |
| 4Bj               | Plaster                    | 0,62                          | Very low                                    |
| 5Bj               | Plaster                    | 2,54                          | Very low                                    |
| 6Bv               | Plaster stucco             | 3,07                          | Low                                         |
| 7Bv               | Plaster stucco             | 6,7                           | Increased                                   |

2.4. Boundary and initial conditions
In HAM (heat-air-moisture) simulations dynamic external boundary conditions for the city of Košice were used according to [27] (Table 3, Figure 5). For the internal boundary condition, an average temperature of 21.2 °C with an amplitude of 1K with a daily maximum of July 3 of 22.2 °C was considered. The internal relative humidity was considered an average value of 60% with an amplitude
of 5% with a daily maximum of 16 September. Based on the moisture survey of the perimeter masonry, the value of \((4Bv)\) was chosen as the initial condition of water content for lime-cement external plaster after recalculation 67.07 kg/m\(^3\).

### Table 3. Boundary conditions

| Parameter          | Value                      |
|--------------------|----------------------------|
| Location           | Košice                     |
| Latitude (°)       | 48.67 North                |
| Longitude (°)      | 21.24 East                 |
| Altitude (m)       | 231                        |
| Mean Temperature (°C) | 10.2                      |
| Max. Temperature (°C) | 31.8                      |
| Min. Temperature (°C) | -12.2                     |
| Mean Relative Humidity (%) | 73.3                   |
| Max. Relative Humidity (%) | 100                     |
| Mean Relative Humidity (%) | 22                      |
| Mean Wind Speed (m/s) | 3.1                      |
| Normal Rain Sum (mm/a) | 469.8                   |

![Image](image.png)

**Figure 5.** Solar radiation and driving rain sum for Košice (from Wufi database)

### 2.5. Material properties

### Table 4. Material properties of existing solid wall

|                  | Thick. (m) | Bulk density (kg/m\(^3\)) | Porosity (m\(^3\)/m\(^3\)) | Specific heat capacity (J/kgK) | Thermal Conductivity (W/mK) | Water vapour diffusion resistance factor (-) |
|------------------|------------|----------------------------|----------------------------|-------------------------------|----------------------------|-------------------------------------------|
| Cement lime plaster | 0.05       | 1900                       | 0.24                       | 850                           | 0.8                        | 19                                       |
| Historical solid brick | 1.4        | 1800                       | 0.31                       | 850                           | 0.6                        | 15                                       |
| Lime plaster      | 0.02       | 1600                       | 0.3                        | 850                           | 0.7                        | 7                                        |

The monitored wall is made of quarry tuff stone, connected by a light-grey mortar with large pieces of quicklime about 1.4 m thick. From the inside, it is plastered with lime plaster with the final surface covering of the white paint. The wall is recessed partially below the ground level and external lime-cement plaster was considered. The material properties of existing wall are presented in Table 4., and material properties of the wall after adding insulation material are presented in Table 5,6.
### Table 5. Material properties of existing solid wall with calcium-silicate insulation th. 50mm

|                       | Thick. (m) | Bulk density (kg/m³) | Porosity (m³/m³) | Specific heat capacity (J/kgK) | Thermal Conductivity (W/mK) | Water vapour diffusion resistance factor (-) |
|-----------------------|------------|----------------------|------------------|--------------------------------|-----------------------------|---------------------------------------------|
| Cement lime plaster   | 0,05       | 1900                 | 0,24             | 850                            | 0,8                         | 19                                          |
| Historical solid brick| 1,4        | 1800                 | 0,31             | 850                            | 0,6                         | 15                                          |
| Cement lime plaster   | 0,02       | 1900                 | 0,24             | 850                            | 0,8                         | 19                                          |
| Ytong Multipor        | 0,05       | 115                  | 0,96             | 850                            | 0,04                        | 4,1                                         |
| Ytong Multipor Adhesive| 0,006     | 833                  | 0,686            | 850                            | 0,155                       | 15,1                                        |

### Table 6. Material properties of existing solid wall with calcium-silicate insulation th. 100mm

|                       | Thick. (m) | Bulk density (kg/m³) | Porosity (m³/m³) | Specific heat capacity (J/kgK) | Thermal Conductivity (W/mK) | Water vapour diffusion resistance factor (-) |
|-----------------------|------------|----------------------|------------------|--------------------------------|-----------------------------|---------------------------------------------|
| Cement lime plaster   | 0,05       | 1900                 | 0,24             | 850                            | 0,8                         | 19                                          |
| Historical solid brick| 1,4        | 1800                 | 0,31             | 850                            | 0,6                         | 15                                          |
| Cement lime plaster   | 0,02       | 1900                 | 0,24             | 850                            | 0,8                         | 19                                          |
| Ytong Multipor        | 0,1        | 115                  | 0,96             | 850                            | 0,04                        | 4,1                                         |
| Ytong Multipor Adhesive| 0,006     | 833                  | 0,686            | 850                            | 0,155                       | 15,1                                        |

### 3. Results and discussions

#### 3.1. Results of simulations

The results of the HAM simulation confirmed our assumption of the beneficial effect of the calcium silicate board used on the inner surface of the historic masonry. The relative humidity on the surface of the structure has been reduced due to the properties of the thermal insulation, which is able to absorb moisture into its core with increased internal relative humidity. (Figure 6-8) The behaviour of the volume of water in the structure is opposite. The behaviour of the volume of water is the opposite. The calcium silicate board prevents the structure from drying inside and thus increases the volume of water in the insulation layer and thus in the historic wall. With an insulation thickness of 100 mm, the drying of the structure inside is even more limited and thus the volume of water in the wall increases.

![Figure 6. Course of temperature, dew point temperature, relative humidity and water content of existing composition of historic masonry](image-url)
In the Figure 9 we see the course of water content in the historic wall for 4 years. The initial water content is approximately 4.5 kg / m³. With the original composition over 4 years, we see a declining trend in the water content, in winter the volume of water increases, in summer it gradually dries out. After applying calcium silicate board thickness 50mm to the inner surface, there is a clear increase in water content over 4 years. In the summer months it tends to dry out to its original content, but we can observe an increase in the water content in the wall structure. After the application of calcium silicate board thickness 100mm, we can already see a more significant increase in the water content compared to the insulation board thickness 50mm. During the summer months, it no longer dries to its original volume and the water content in the structure increases every year. Data from 24.4.2023 are marked, where for 4 years we can see the maximum value of the water content in the structure at 50mm and 100mm insulation.
3.2. Discussion
The measured values of mass water content were applied as the initial conditions of the long-term HAM simulation. Therefore, the state of the structure at the beginning of the heat transfer process became realistic. The influence of water content in the structure as an initial condition in the hygrothermal simulation is well known [24]. We can therefore consider the results of long-term simulations to be reliable. The result of the simulation is the water content in the structure after the application of two different thicknesses of internal insulation and without insulation of the perimeter masonry wall. The water content increases with increasing thickness of the thermal insulation and its long-term accumulation occurs. With a wall thermal insulation thickness of 100 mm the structure inability of the drying in summer is visible. The structure slowly gets rid of the in-winter months accumulated amount of water. In contrary, with a thermal insulation thickness of 50 mm, the structure can reduce its percentage water content between periods from 0.28 to 0.25%. Findings from the results of long-term simulations indicate that it is necessary to optimize the thickness of thermal insulation with respect to the accumulation of water in the structure.

The original wall with a thickness of 1.47 m has a heat transfer coefficient \( U = 0.398 \text{ W/}(\text{m}^2\text{K}) \). After insulation with a calcium-silicate capillary-active insulation board 50 mm thick was used, the heat transfer coefficient decreased to \( U = 0.274 \text{ W/}(\text{m}^2\text{K}) \). When 100mm thick insulation was used, this value was reduced to 0.21 \( \text{ W/}(\text{m}^2\text{K}) \). (Figure 10)
4. Conclusions

Historical masonry of massive thickness is capable of significant accumulation of heat but also of water. The long-term simulation results of water content accumulation in the structure after insulation confirm the fact that internal insulation prevents drying into the interior in summer period. There is a decrease in temperature inside the masonry due to thermal insulation from the interior when the structure is subcooled and poorly heated. The decrease in temperature inside the masonry together with the reduced ability of the masonry to dry into the interior in the summer result in an increased rate of accumulation of water content in the insulated structure. The percentages of masonry water content after insulation and after two years do not exceed the level - very low humidity. We can conclude that even when the thickness of 100 mm from the inside is insulated the construction will remain functional in heat-air-moisture terms of view. However, it should be noted that the assessment is carried out in a one-dimensional hygrothermal transport. With the multidimensional details of structures and various structural conditions of historic buildings undesirable effects of internal insulation can occur locally. The task for the future work is experimentally in-situ verification of the performance of the exterior wall structures of the building before and after the insulation. The obtained data from further research can be used to achieve a comprehensive picture of the hygrothermal behaviour of the masonry of historic buildings on which the internal insulation was carried out.

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