

Hygrothermal Analysis of Mineral Wool Insulated Building Constructions Based on *In Situ* Measurements

Balázs NAGY^{1,a*}, Dóra SZAGRI^{1,b} and Dániel BAKONYI^{2,c}

¹Budapest University of Technology and Economics, Faculty of Civil Engineering, Department of Construction Materials and Technologies, Műegyetem rkp. 3. K.I.85., 1111 Budapest, Hungary

²Budapest University of Technology and Economics, Faculty of Architecture, Department of Building Constructions, Műegyetem rkp. 3. K.II.40., 1111 Budapest, Hungary

^anagy.balazs@epito.bme.hu, ^bszagridora@edu.bme.hu, ^cdbakonyi@epsz.bme.hu

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Abstract. The paper discusses an experimental hygrothermal analysis of differently constructed additional mineral wool wall and attic insulation of a family house in Hajdúnánás, Hungary. The walls of the building were insulated in two different ways: half of the façade was insulated with Knauf stone mineral wool insulation boards glued to the walls in a continuous mortar bed as recommended, and on the other side of the same façade, the boards were glued only with patches of mortar. In the attic of the same building, one part of the attic was insulated by using Knauf glass mineral wool insulation batts along with vapour permeable underlay membrane as recommended, while the other part was constructed without underlay. Temperature and relative humidity sensors were placed between the layers and heat flux sensors were installed on the internal surfaces of the two differently constructed wall and attic insulations. An external meteorological station was installed on an unused chimney of the building. Besides the structural sensors, temperature and relative humidity sensors were installed in each room, and the energy consumption of the building was also monitored during the measurements. For control values, we monitored the internal hygrothermal conditions and the energy consumption of an identical but uninsulated family house only 8 km away in Hajdúdorog, Hungary. In the article, we analyse the heat and moisture transport through the building constructions and the energy consumption of the family house according to the recorded data of a full heating season.

Introduction

In 2013, the Hungarian subsidiary of Knauf Insulation Company, a manufacturer and distributor of thermal insulation products, initiated a new experiment and publicity campaign by the name of ‘Insulate my home’. This was carried out in order to popularize the use of thermal insulation for reducing energy consumption in existing, privately owned residential buildings. They contacted the Department of Building Construction at the Budapest University of Technology and Economics, as well as several companies in the industry, to provide scientific and technical backing for the project. The primary aim was to demonstrate the energy consumption reduction resulted by intensive thermal insulation in a clear and easy to understand manner. For this purpose, two families and their two detached family homes were selected during a public competition. The two buildings were almost identical in size, layout and construction and were located within a few kilometres from each other in the Northern Alföld region of Hungary. The first building, henceforth building ‘A’, in the town of Hajdúnánás was insulated at the company’s expense, while building ‘B’ in the nearby town of Hajdúdorog was kept uninsulated as a control building. A monitoring system was devised and set up to record the relevant quantities. A further aim of the project was to demonstrate the importance of proficient design and craftsmanship the reach the quality performance of thermal insulations. Therefore, an additional research plan was proposed to comparatively measure the in-situ hygrothermal performance of two variants of both the stone mineral wool based ETICS and the glass mineral wool based attic insulations used in building ‘A’. At the wall we aimed to show the adverse effects the lack of a proper adhesive mortar layer between the wall and the insulation, i.e. if a thin layer of air is formed behind the insulation. While most of the building was insulated

following the proper technique of gluing the insulation boards in a continuous mortar bed (at least at their joints), on a small surface on the South-Eastern façade of the building (approx. 10 m²) the insulation was built with only patches of adhesive mortar. As far as the attic insulation is concerned, we intended to study the effect that the use of a vapour permeable roofing underlay membrane provides protection for the thermal insulation. As with many other existing detached family houses the insulation of the slab between the interior and the attic space was made without the renovation of the roof and the addition of a roofing membrane underneath the tiles, therefore moisture (as well as the wind) was able to penetrate into the attic space.

Methodology

Measurement of the boundary conditions. A weather station (see Fig. 1) measured the external boundary conditions as dry-bulb temperature, relative humidity, atmospheric pressure, wind speed and direction, as well as precipitation above the roof of building 'A' at every 15 minutes interval. In both buildings, internal boundary conditions as dry-bulb temperature and relative humidity were recorded in all the rooms, and the families were instructed to follow similar heating and ventilation patterns for the duration of the project. From the measured values - after checking and cleaning the data - we created hourly climate data set for further research.



Fig. 1 From top left to bottom right: house in Hajdúnánás before the insulation process; thermal energy meter built into the heating system; sensors in the attic; weather station on an unused chimney; sensor installation on the façade; heat flux meter on the inner wall

Measurement of the attic and walls. The two attic and façade wall insulation variations and the sensor installation process are represented in Fig. 1. The heat flow densities were measured with an Omega HFS-3 thin plate heat flux meter and a 16-bit ADC with an integrated surface temperature sensing K-type thermocouple at the interior surface of the wall. The temperature and relative humidity sensors were Sensirion SHT 75 type with a temperature measurement tolerance of ± 0.5 K and a humidity tolerance of ± 2 %. The external surface temperature was measured with a digital temperature sensor with similar accuracy. Both measured façade surfaces were oriented in the same direction (South-East) and the measured cross sections were in the same wall (belonging to the same room). The two constructional attic and façade variations and the sensor placement are represented in Fig. 2.

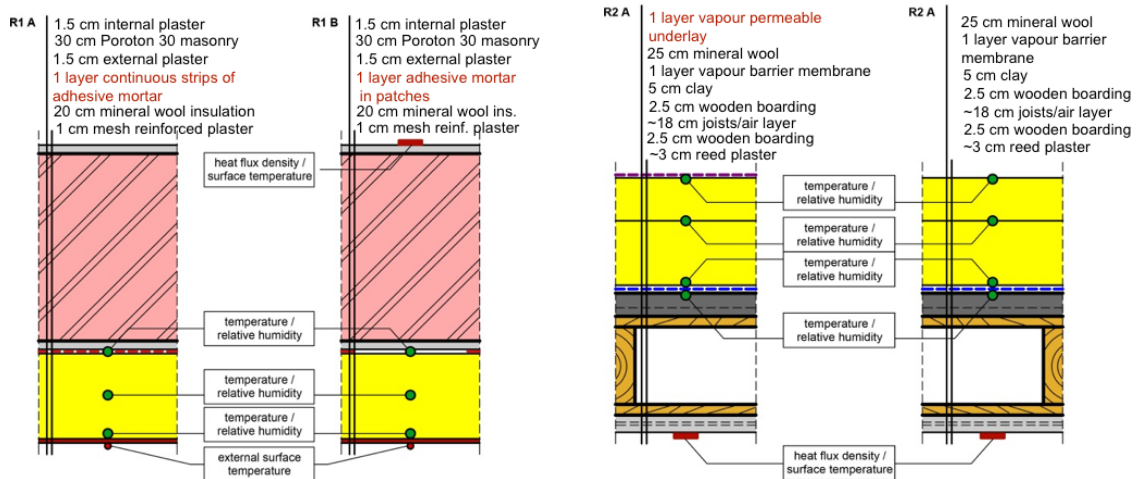


Fig. 2 Left side: sections of the investigated ETICS variants and the sensor placement; Right side: sections of the investigated attic insulation variants and the sensor placement

Measurement of the energy used for heating. The energy used for heating was also logged every 15 minutes period with a thermal energy meter built into the heating system (both houses had a gas boiler and radiators with hot water as heating medium), see Fig. 1., while gas consumption was calculated using standardized values of boiler efficiency to provide an easier comparison. The energy monitoring took place for a single heating season between 27 September 2013 and 31 March 2014. A summary of the results can be found on a Hungarian webpage [1].

Temperature and relative humidity data evaluation. To illustrate our measured dataset from 12 October to 20 May we used data contouring. We represented the values in a 3D map to show the temperature and relative humidity distributions of the building structure. To determine the values between the measured points Kriging interpolation method was applied. Kriging is a geostatistical interpolation technique that considers both the distance and the degree of variation between known data points when estimating values in unknown areas [2]. It can be seen as a point interpolation which requires a point map as input and results in a raster map with estimations as output and optionally an error map. The results are shown in Fig. 4 and Fig. 6.

Calculation of the momentary thermal conductivities. The constantly changing value of thermal conductivity can be determined from temperature and relative humidity data, which was recorded during the measurements. The value of the thermal conductivity of each layer can be determined according to ISO 10456:2007 [3] based on the temperature and relative humidity values measured in the layers and at the layer boundaries:

$$\lambda_2 = \lambda_1 \cdot F_T \cdot F_m \cdot F_a = \lambda_1 \cdot e^{f_T(T_2-T_1)} \cdot e^{f_u(U_2-U_1)} \cdot 1 \quad (1)$$

where λ_2 is the adjusted thermal conductivity, λ_1 is the declared value of thermal conductivity, F_T , F_m and F_a are the temperature, moisture and age conversion factors, latter one was set to 1 since no further ageing was considered. f_T is temperature conversion coefficient, T_2 and T_1 represents the temperature difference between the first and second set of conditions, f_u is moisture conversion coefficient, U_2 and U_1 are moisture content in case of the first and second set of conditions. For the moisture conversion, the connection between the RH in a material and the moisture content is the moisture storage function.

Calculation of the thermal transmittances. Under steady-state conditions the thermal transmittance (U-value) can be obtained by measuring the heat flow density through an element, and recording the temperature on both sides of the element. Since steady-state conditions are never achieved in practice, there are many different methods to eliminate the difficulty the calculation, in this case: we should assume that the mean values of heat flow density and temperatures over a long-time period give an estimate for the steady-state condition. There are several stages of U-value measurement process including the selection and calibrating of heat flow meters and temperature

sensors, measurements and analysis of the data. For calculating the U-value from measured temperature data and heat flow densities, averaging method was used [4].

There are three conditions and the test can be completed, when these conditions are fulfilled [5]. The first condition is that the duration of the test must exceed 72 hours (three days) if the temperature is stable around the heat flow meter. The second is that the R-value obtained at the end of the test cannot deviate more than $\pm 5\%$ from the value obtained 24 h before. The last condition is that the R-value obtained by analysing the data from the first-time period during $INT(2 \cdot DT/3)$ day does not deviate more than $\pm 5\%$ from the values obtained from the data of the last time period of the same duration, where DT is the duration of the test in days and INT is the integer part.

This method assumes that the U-value can be obtained by dividing the mean heat flow density by the mean temperature difference. An estimated U-value is obtained by the following formula:

$$U = \frac{\sum q}{\sum (T_i - T_e)} \quad (2)$$

where q is the heat flow density, T_i is the internal and T_e is the external air temperature. U-value is also calculated by the following equations from surface temperature or from thermal resistance values:

$$U = \frac{q}{T_i - T_e} = h_{si} \cdot \frac{T_i - T_s}{T_i - T_e} = \left(h_{ci} + \varepsilon \cdot \sigma \cdot \frac{T_i^4 - T_s^4}{T_i - T_s} \right) \cdot \frac{T_i - T_s}{T_i - T_e} = \frac{1}{\frac{1}{h_{ci} + h_{ri}} + \sum \frac{d_j}{\lambda_{2,j}} + \frac{1}{h_{ce} + h_{re}}} \quad (3)$$

where h_{ci} is the internal convective and h_{ri} is the radiative part of the h_{si} internal surface heat transfer coefficient, ε is the emissivity factor of the surface, σ is the Stefan-Boltzmann constant, T_i and T_e stands for the internal and external air temperature, T_s is the temperature of the measured internal surface, λ_2 is the temperature and relative humidity adjusted thermal conductivity of the d_j thick layer, h_{ce} is the external convective and h_{re} is the radiative part of the external surface heat transfer coefficient according to ISO 6946:2007 [6].

Results

Indoor and outdoor conditions. Indoor measurements (see Fig. 3) show that during the measuring process there was higher inner temperature and lower relative humidity in the bedroom than in the children's room. Outdoor and attic temperature were fairly close to each other. It is important to mention that the relative humidity in attic greatly increased at the beginning of February. The anomaly shown in Fig. 7 and Fig. 8 can be explained by an intense rainfall in the time period. The average wind speed during the measurements was 4.6 m/s, however the maximum was 27.6 m/s.

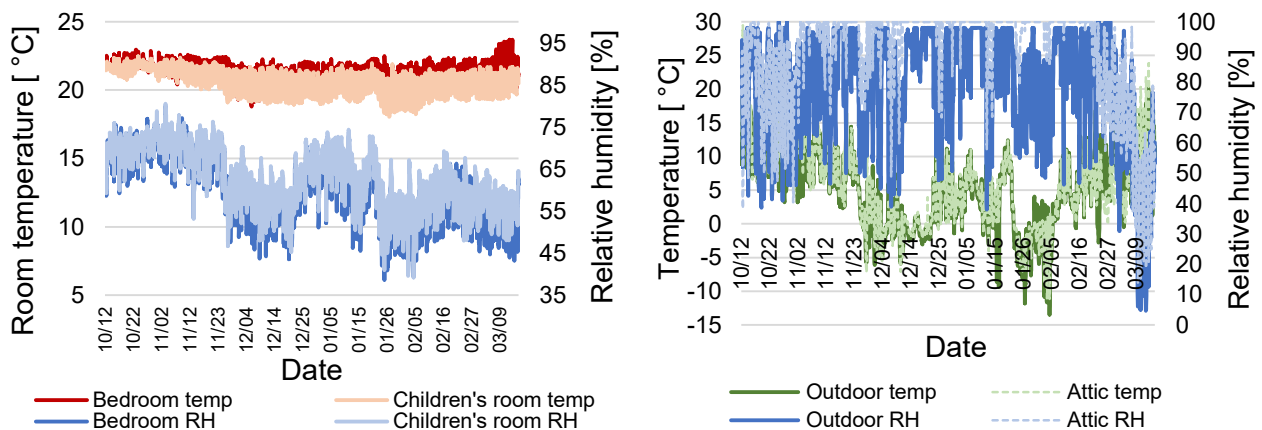


Fig. 3 Left side: internal conditions (temperature and relative humidity in bedroom and children's room); Right side: external conditions (outdoor and attic temperature and relative humidity)

Wall sections. Fig. 4 a-d show the measured and Kriging interpolated temperature and relative humidity distribution in the cross sections over time. The average temperature in the ETICS layer was 12.5 °C when applying continuous strips of gluing mortar and 14.6 °C when the insulation was fixed on the surface by mortar patches, while the average RH was 77% and 83% respectively. Fig. 4 e-f shows the difference in temperature and relative humidity across the sections over time, respectively. It is observable that there was a temperature and relative humidity differences in the insulating layers. The minimum temperatures in ETICS were 2.51 °C and 5.48 °C and the maximum temperatures were 12.51 °C and 14.6 °C while in RH values, the minimum were 32% and 30%, while the maximum were 77% and 83%.

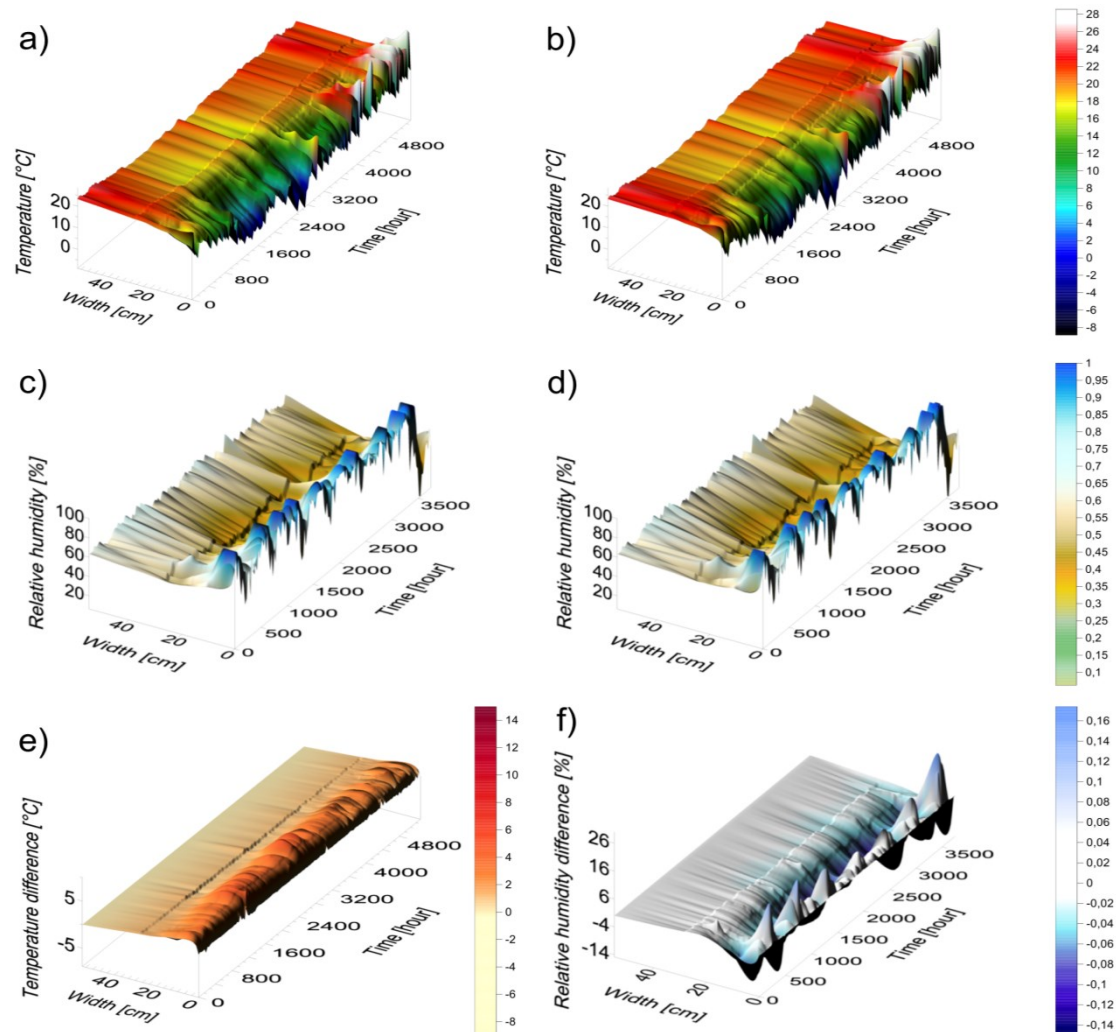


Fig. 4 Temperature distribution in the structure a) continuous strips glued insulation, b) patches glued insulation; RH distribution c) continuous strips glued insulation, d) patches glued insulation; e) temperature and f) RH difference between the structures

Based on Fig. 5, the temperature in the adhesive mortar layer is higher by about 1 °C, when the insulation is glued with patches to the wall. The relative humidity distribution in the adhesive continuous mortar layer is 43% and 40.47% in case when only mortar patches were used.

The average thermal conversion factor for continuous mortared insulation was 1.009, while the patches glued insulation's value was 1.016, and the average moisture conversion factor was 1.012 and 1.011. It is observable that the temperature conversion factor increased significantly, while the moisture conversion factor decreased a little. The average thermal conductivity of the ETICS during the whole measurement must be corrected by the conversion factors, the continuous strips glued ETICS performed $0.040 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$ while patches glued ETICS resulted $0.041 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$.

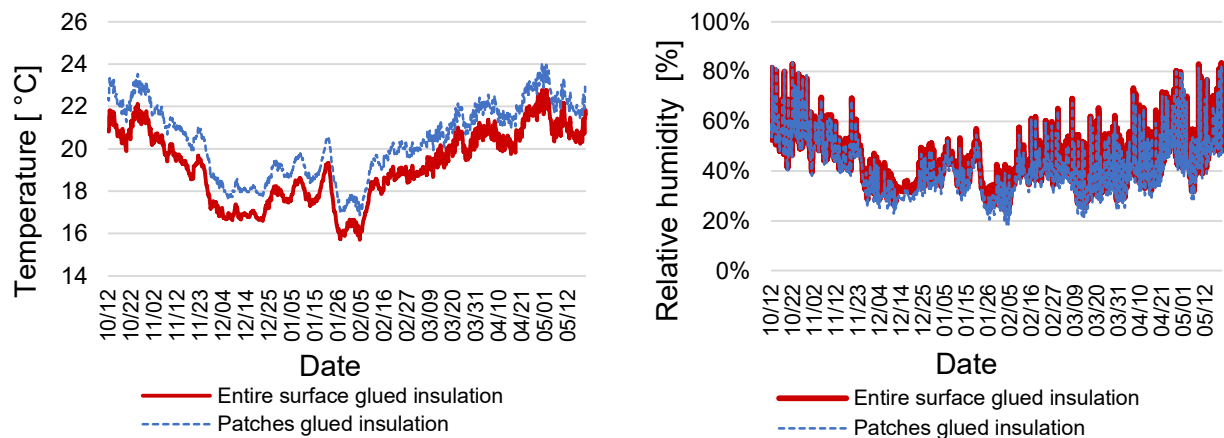


Fig. 5 Temperature (left) and relative humidity distribution (right) in the adhesive mortar layers

Attic sections. The attics form a transition between the interior spaces and outdoor, the roof protects the thermal insulation on the ceiling from the impacts of the weather, but this protection is not 100% especially when no roof foil is used. The temperature and relative humidity across the sections and the difference between the two construction variants are represented in Fig 6.

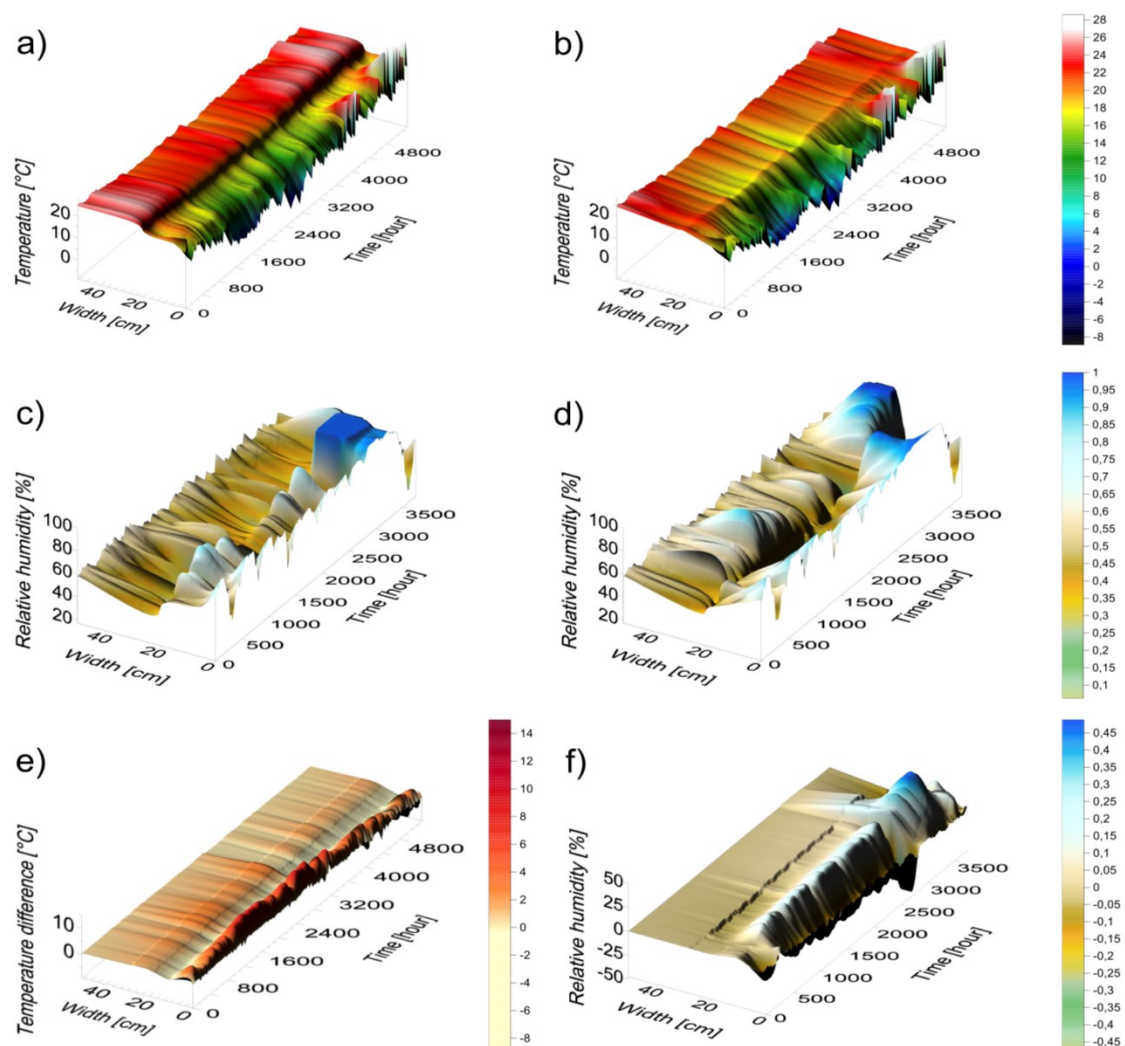


Fig. 6 Temperature distribution in the structure a) with vapour permeable roofing underlay, b) without vapour permeable layer; RH distribution c) with vapour permeable roofing underlay, d) without vapour permeable layer; e) temperature and f) RH difference between the structures

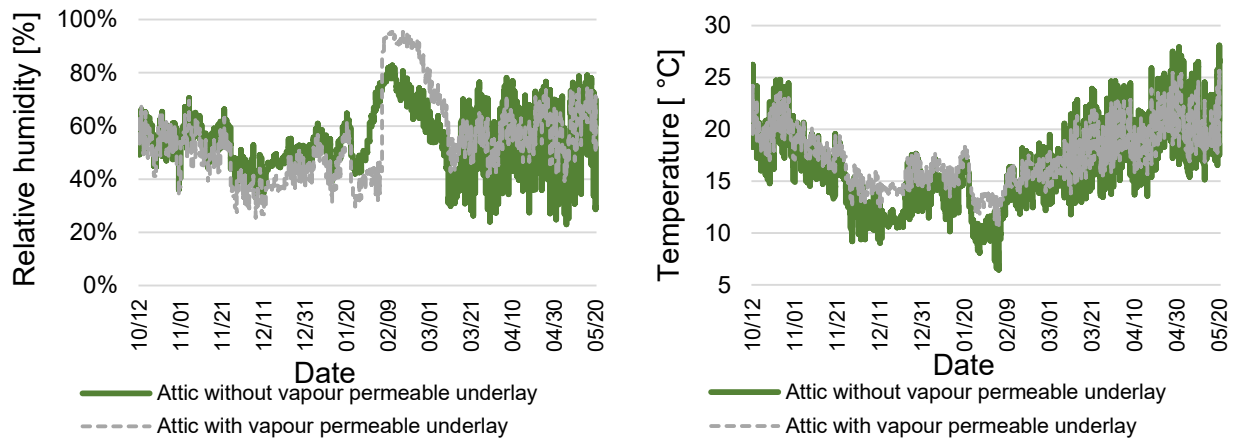


Fig. 7 Temperature and relative humidity in the bottom section of the insulation

Fig. 7 demonstrates that the relative humidity is lower in the structure with vapour permeable underlay membrane until 5 February. As mentioned before, at that time there was an intense rainfall, and since the roof structure was built without roofing membrane under the tiles, this could cause the insulation on the attic to be damp. The thermal conductivities, shown in Fig. 8 were calculated using Eq. 1 and shows the effect of the higher moisture content due to higher relative humidity. Before 5 February the structure with vapour permeable underlay had lower thermal conductivity, due to the lower RH values measured in the insulating material, the moisture content of the material was lower. After the rainfall incidence, the insulating layer took up moisture quickly, since it had membrane on it, it could not dry out properly until the end of the measurement. The other examined section, without the underlay also took up moisture after the incidence, but it could dry out better, resulting in lower thermal conductivities. Based the measured temperature and RH data the adjusted thermal conductivity of the insulation was $0.044 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$ for both sections, which was 14% higher, than the declared thermal conductivity.

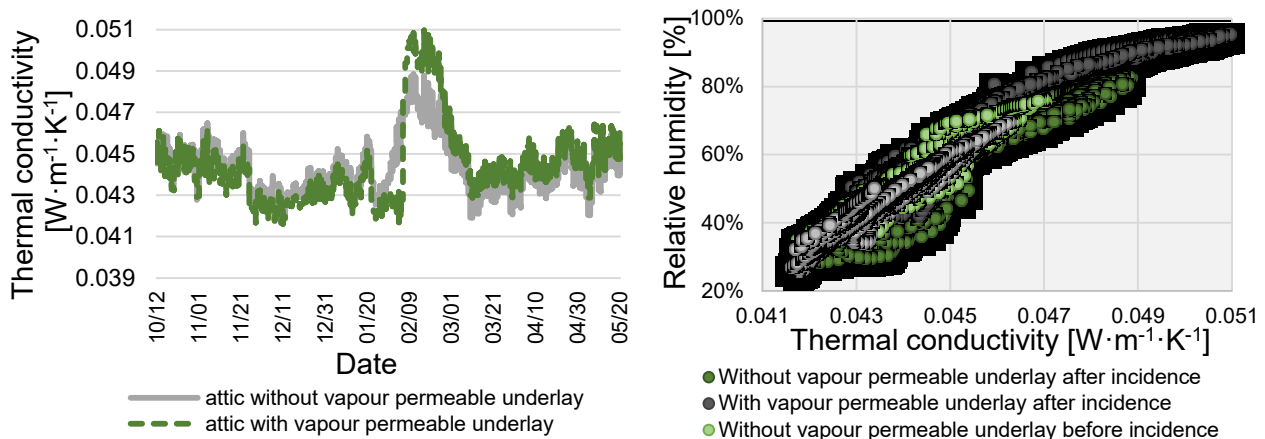


Fig. 8 Thermal conductivity and relative humidity over thermal conductivity of the attic insulations

Thermal transmittances. Using Eq. 2, the U-values of the wall sections and the ceilings were calculated. These U-values take the dynamic boundary conditions, layer temperatures and RH changes into account. The average U-value of the continuous mortared wall section was $0.158 \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$ and the other section was $0.16 \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$, while the steady calculated U-value was $0.15 \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$. The average U-value of the attic sections was $0.191 \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$ respectively, while the calculated one was $0.17 \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$.

Using the measured data, h_s surface heat transfer coefficients as well as R_s surface resistances can be obtained. The average internal horizontal surface heat transfer coefficient for the walls was $h_{si} = 8.49 \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$ ($R_{si} = 0.118 \text{ m}^2 \cdot \text{K} \cdot \text{W}^{-1}$) and the external surface heat transfer coefficient was $h_{se} = 26.82 \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$ ($R_{se} = 0.037 \text{ m}^2 \cdot \text{K} \cdot \text{W}^{-1}$) which values are close to the standard's values [6].

Energy used for heating. The heating energy was logged in a single heating period (27 September 2013 – 31 March 2014) with a thermal energy meter built into the heating system (see Fig. 9). The energy consumption reached its peak in both cases at the end of January. During this period the maximum energy consumption was 0.58 GJ in the uninsulated house during a day, and it was less than a half of this, 0.26 GJ in the insulated house. If the overall energy consumption is summed up, the insulated house in Hajdúnánás used 23.73 GJ while the uninsulated house in Hajdúdorog used 52.60 GJ; therefore we can see that the insulated house used almost 55% less energy than the uninsulated one during the investigated period.

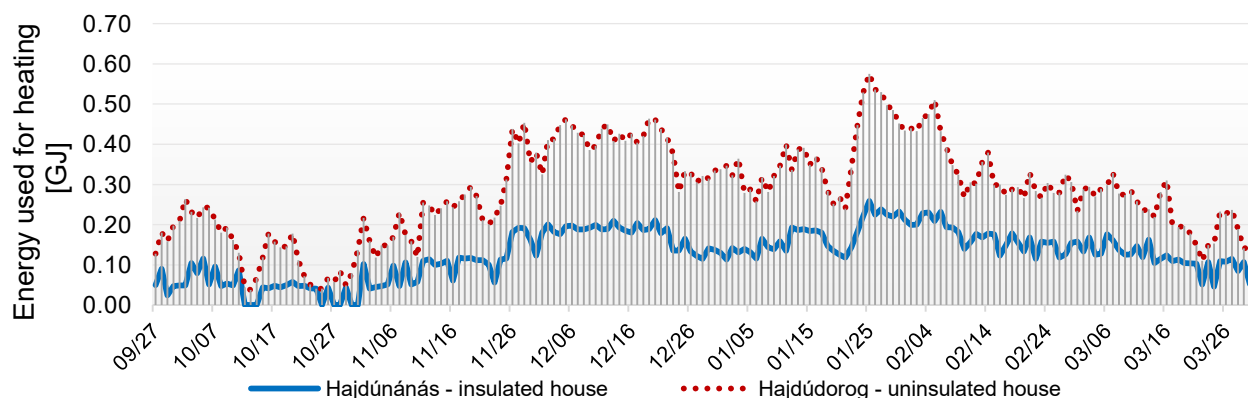


Fig. 9 Energy used for heating in a single heating season

Summary

In the paper, we analysed measured datasets of a family house during an entire heating season. We examined the temperature and RH distributions, thermal conductivities and thermal transmittances of two variants of two building constructions. Based on results, it can be stated that the different construction technologies of ETICS resulted in distinct temperature and RH values in the ETICS layer. The vapour permeable membrane on the attic insulation is useful when the membrane and the covered insulation did not get touch with water or high relative humidity. The membrane could slow down the dry out process of the insulation resulting higher thermal conductivities. Based on the results, further detailed analysis is suggested. The measurements also proved that insulating a family house could end up saving more than 50% energy use.

Acknowledgement

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