Computational simulation of hygrothermal processes in historical building envelopes provided with interior thermal insulation

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Abstract. Interior thermal insulation systems are an integral part of retrofitting works, especially when historical buildings are taken into account. In this paper, three different insulation materials (mineral wool, calcium silicate, and sheep wool) were investigated in order to assess their suitability for the application in historical buildings. First, the basic physical, hygric and thermal properties of those materials were measured in laboratory conditions and then a series of computational simulations was carried out. Finally, based on the simulation results, the hygrothermal response was analyzed and several conclusions were drawn. The presented results proved all materials suitable for application in interior thermal insulation systems but some differences in the hygrothermal response of individual materials were observed.

1. Introduction

Historical buildings are considered in most nations as valuable heritages from past generations and cultures. In some cases, it can be talked about structures of incalculable value. However, in the modern world, those buildings often fail to meet current standards and therefore require some retrofits to be applied.

A proper decision on renovation measures is very important for the overall effectiveness of retrofitting works. When thermal insulation is considered as a renovation measure for an old historical building, the engineers are usually restricted to the applications of additional insulation layers on the interior side of the building enclosures. However, the interior thermal insulations may increase a potential water vapor condensation hazard in the buildings' interior and thus to act counterproductively, as the quality of indoor environment may be significantly worsened. In order to prevent the negative actions, a serious hygrothermal assessment must be done. Due to high complexity of the assessment procedure, the advanced technique based on perfect knowledge on thermal and hygric properties of insulation materials together with the application of computational modelling seems to be most effective for this kind of task.

In this paper a series of computational simulations is carried out and the hygrothermal response of interior thermal insulation layers in reconstructions of historical buildings on the Czech territory is assessed. For that reason, three different insulating materials were selected (calcium silicate, hydrophilic mineral wool, and sheep wool) and their thermal and hygric properties were analyzed in the laboratories, in order to obtain accurate input data for the computational model.

2. Studied insulation systems

The cross-section of a historical building wall is shown in figure 1. In that cross-section following materials were assumed: sandstone from Libnava quarry (SL), interior thermal insulation (calcium silicate, hydrophilic mineral wool, or sheep wool), interior and exterior plaster, and connecting layer between load-bearing structure and thermal insulation. The interior plaster and exterior plaster were made from the same material that was developed for renovation of historical masonry.
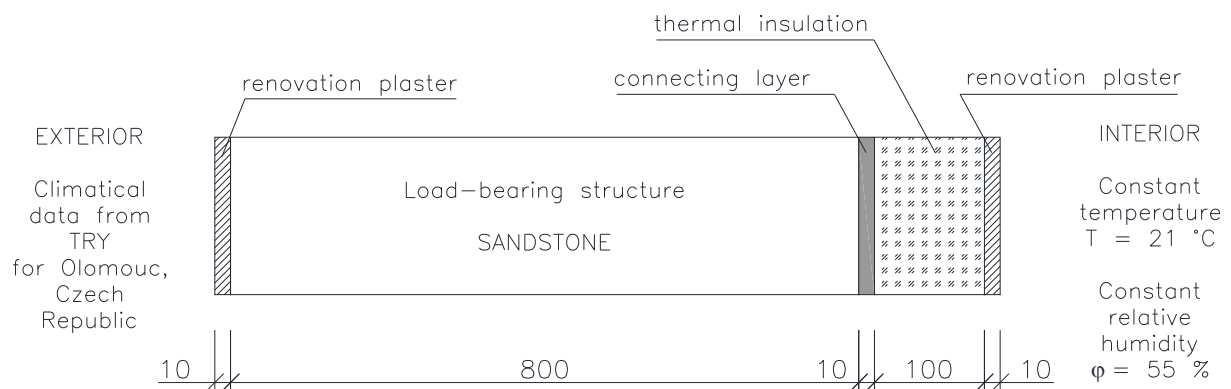

Figure 1. Horizontal cross-section of investigated historical wall

3. Experimental

The involved materials were subjected to laboratory analysis in order to obtain basic material parameters that are necessary for further investigation of their hygrothermal response. The material properties of calcium silicate (CS) and sheep wool (SW) were determined in the laboratories of the Department of Materials Engineering and Chemistry, Faculty of Civil Engineering, Czech Technical University in Prague within the frame of this project and were stored in the material database. The other materials namely sandstone (SL) [1], mineral wool (MW) [2], connecting layer (M2) [3], interior (IP) and exterior (EP) plasters [4] were analyzed in the same laboratories, but have been published earlier. All material parameters were measured according to the methodology described in [5]. The basic physical, heat and moisture transport and storage properties of sandstones are given in table 1, where ϱ is the bulk density, ψ the porosity, c_{dry} the specific heat capacity in dry conditions, c_{sat} the specific heat capacity in saturated conditions, $\mu_{dry\ cup}$ the water vapor diffusion resistance factor in dry conditions, $\mu_{wet\ cup}$ the water vapor diffusion resistance factor in wet conditions, λ_{dry} the thermal conductivity in dry conditions, λ_{sat} the thermal conductivity in water saturated conditions.

In addition to data presented in table 1, the sorption isotherms and moisture diffusivities of all involved materials were measured as well.

Table 1. Basic physical properties involved materials

Parameter	SL	MW	CS	SW	M2	IP/EP
ϱ (kg m^{-3})	2191	270	231	15	1430	1690
ψ (%)	17.9	96.5	90.7	98.7	42.6	34.1
c_{dry} (J kg^{-1} K^{-1})	721	810	1248	972	1020	877
c_{sat} (J kg^{-1} K^{-1})	1127	3850	3523	972	1020	877

$\mu_{dry\ cup}$ (-)	11.60	2.62	2.11	2.83	6.60	29.00
$\mu_{wet\ cup}$ (-)	7.40	1.34	1.65	2.36	6.20	11.60
λ_{dry} (W m^{-1} K^{-1})	2.71	0.036	0.0682	0.045	0.481	0.886
λ_{sat} (W m^{-1} K^{-1})	4.64	0.705	0.5026	0.045	2.022	2.190

4. Computational

4.1. Mathematical model

For the investigation of hygrothermal performance of studied constructions a modified Künzel's mathematical model was used [6]. The modified mathematical model is able to distinguish more precisely between liquid and gaseous phase of moisture transport and thus brings higher accuracy to the calculations [7]. Balance equations are expressed as

$$\frac{dH}{dT}\frac{\partial T}{\partial t} = div(\lambda\, gradT) + L_v\, div(\delta_p\, grad\, p_v), \tag{1}$$

$$\left[\rho_w\frac{dw}{dp_v} + (n-w)\frac{M}{RT}\right]\frac{\partial p_v}{\partial t} = div[D_g\ grad\, p_v], \tag{2}$$

where H (J·m^{-3}) is the enthalpy density, T (K) the absolute temperature, λ (W·m^{-1}·K^{-1}) the thermal conductivity, L_v (J·kg^{-1}) the latent heat of evaporation of water, δ_p (s) the water vapor diffusion permeability, p_v (Pa) the partial pressure of water vapor in the porous space, ϱ_w (kg·m^{-3}) the density of water, w (m^3·m^{-3}) the moisture content by volume, n (-) the porosity, M (kg·mol^{-1}) the molar mass of water vapor, and R (J·K^{-1}·mol^{-1}) is the universal gas constant. D_g (s) is the global moisture transport function defined as

$$D_g = B \cdot D_w \rho_w \frac{dw}{dp_v} + A \cdot \delta_p, \tag{3}$$

where A and B in Eq. (3) are the membership functions defining the transition between particular phases of water, which can be formulated as

$$B = \begin{cases} 0 & \varphi \in \langle 0;0.9) \\ 32\left[\left(\frac{1}{p_{v2}-p_{v1}}\right)(p_v - p_{v1})\right]^6 & \varphi \in \langle 0.9;0.938) \\ 1-32\left[\left(\frac{1}{p_{v2}-p_{v1}}\right)(p_{v2} - p_v)\right]^6 & \varphi \in \langle 0.938;0.976) \\ 1 & \varphi \in \langle 0.976;1\rangle \end{cases}, \tag{4}$$

$$A = 1 - B, \tag{5}$$

where the partial pressures of water vapor p_{v1} and p_{v2} (Pa) define the transition region. In this paper the values of p_{v1} and p_{v2} corresponded to the values of relative humidity of 90 % and 97.6 %, respectively.

The simulations were carried out on the one-dimensional cross section depicted in figure 1 using the TempMoist2D simulation tool. The tool is based on the general finite element package SIFEL (SImple Finite Elements) [8].

4.2. Boundary conditions

Boundary conditions in the interior were set constant as 21 °C and 55 % relative humidity. On the exterior side, the climatic load in a form of Test Reference Year (TRY) for Olomouc, Czech Republic was applied. The TRY was obtained from the Czech Hydrometeorological Institute (CHMI) which is the official authority for climatology, hydrology and atmosphere quality in the Czech Republic. The weather data obtained from CHMI as well as other sources are stored in weather database [9]. The data contained hourly values of temperature, relative humidity, wind speed, wind direction, precipitation and solar radiation. The summary of temperature, relative humidity and amount of precipitation is provided in table 2.

Table 2. Summary of applied weather data

Month	Temperature (° C)	Relative humidity (%)	Rainfall (mm)
Jan	-2.02	85.52	30.70
Feb	2.40	78.76	8.10
Mar	4.54	69.08	71.50
Apr	10.47	68.16	42.20
May	15.09	68.15	38.09
Jun	18.49	69.23	67.21
Jul	20.16	69.26	107.80
Aug	20.73	69.09	63.00
Sep	14.52	77.80	20.50
Oct	10.30	81.17	18.00
Nov	4.44	90.23	68.50
Dec	-1.64	86.50	35.30

5. Results and discussion

The results of computational simulations performed by HEMOT code are presented below in figures 2 and 3. All the computer simulations were accomplished for 10 years in order to limit the effect of initial conditions in the studied walls. The hygrothermal performance was captured in four different days representing all periods of the year. The data are presented for 1 February (winter), 1 May (spring), 1 August (summer) and 1 November (autumn).
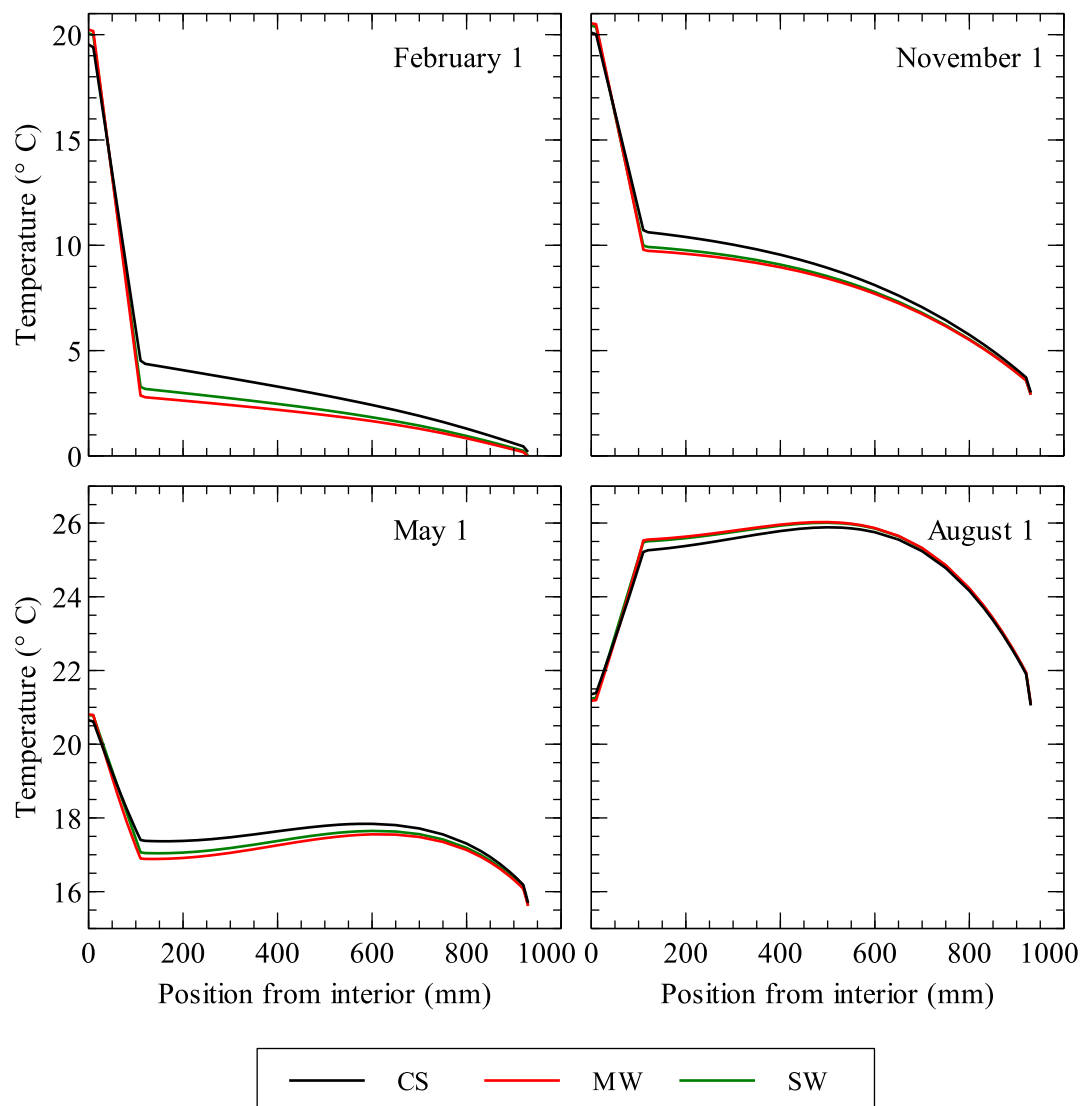
Figure 2. Temperature distribution in the studied envelopes

As it is obvious from figure 2 the highest temperatures in the wall can be observed mostly for calcium silicate and lowest for mineral wool. This might be crucial for the possible condensation of water vapor. However, the differences in thermal performance are not significant as they vary about 1 – 3 °C. Furthermore, the closer to the exterior surface the more the values approach each other.

When the interior surface temperature is considered, the highest values can be observed for mineral wool (20.24 °C in February and 20.54 °C in November) and lowest for calcium silicate (19.53 °C in February and 20.09 °C in November). The sheep wool is very close to the mineral wool in this respect.
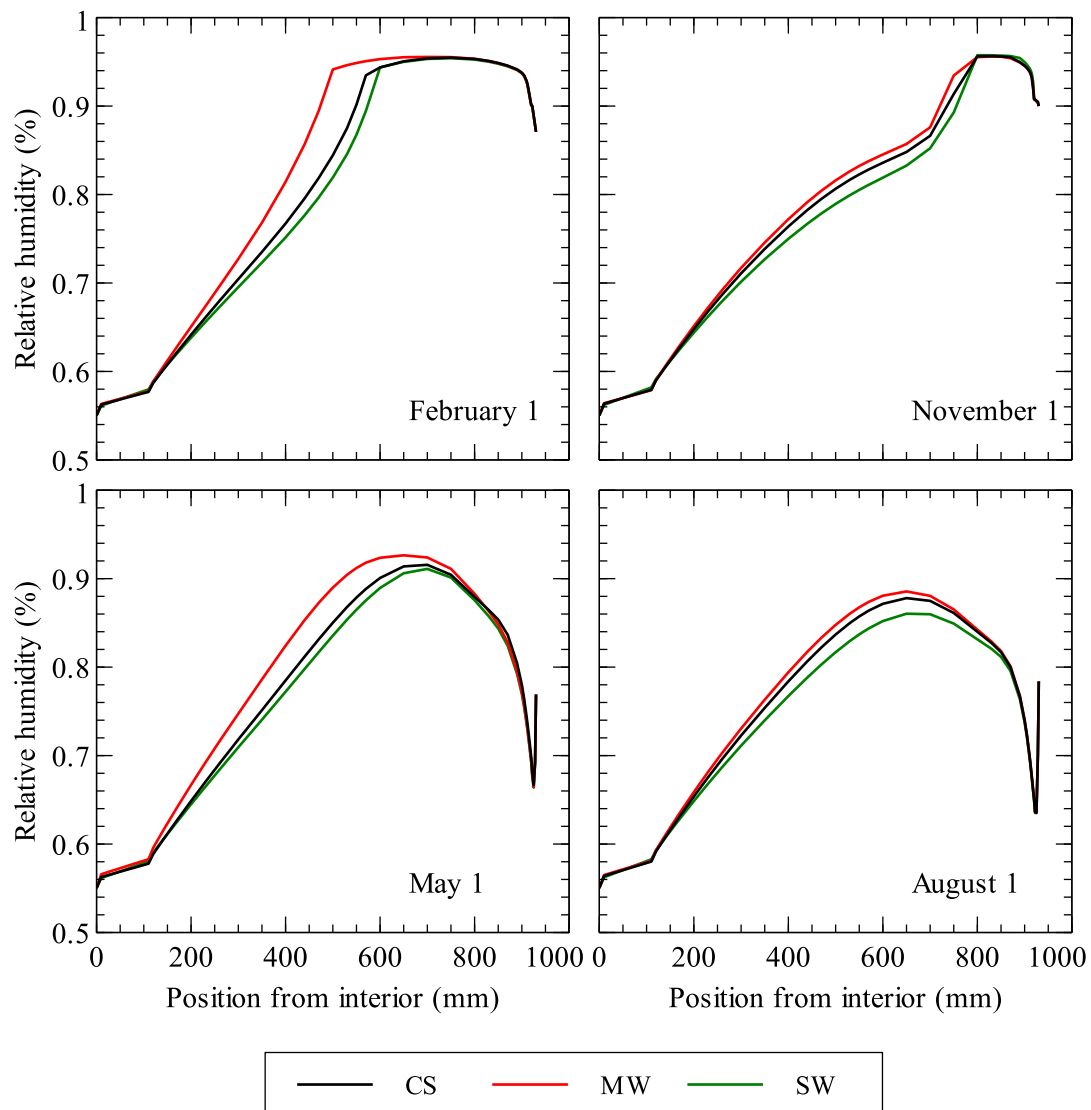
Figure 3. Relative humidity distribution in the studied envelopes

The hygric performance is probably more important than thermal as all studied thermal insulation materials proved very similar thermal parameters. However, the hygric properties of those materials can significantly influence the response of whole structure. From that point of view the best results can be observed for sheep wool which exhibits the lowest values of relative humidity in all investigated seasons. On the other hand, the highest values were observed for mineral wool which implies the highest risk of water vapor condensation.

6. Conclusions

Three different thermal insulation materials were investigated in this paper as possible candidates for interior thermal insulation systems of historical buildings. Based on the presented results it can be concluded that all of them were suitable for the application within retrofitting works but some small differences in the hygrothermal response were observed:

- Mineral wool proved best thermal insulation capabilities among the investigated materials
- The highest interior surface temperature was observed for mineral wool and sheep wool

- The best hygric performance was observed for sheep wool, whereas mineral wool showed the worst performance, especially in the winter period.

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