Coupled heat and moisture transport in a building envelope on cast gypsum basis

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Abstract

Flue gas desulphurization (FGD) gypsum can be potentially used as a material for load bearing structures. In this paper, a computational assessment of hygrothermal performance of a building envelope based on several modifications of FGD gypsum is presented. In the computer simulations of temperature and relative humidity fields, three variations of FGD gypsum wall, based on the raw material and on two types of hydrophobized gypsum, with the thickness of 300 mm, are solved. The thermal insulation function of the wall is achieved by exterior thermal insulation boards with the thickness of 100 mm, which are considered in four variants. Insulation I is hydrophilic material with a low value of hygroscopic moisture content on mineral wool basis, Insulation II capillary active material with higher value of hygroscopic moisture content on calcium-silicate basis, Insulation III hydrophobic material with a low value of water vapor resistance factor on mineral wool basis and Insulation IV hydrophobic material with higher value of water vapor resistance factor on polystyrene basis. Lime plaster with the thickness of 10 mm is used on the exterior wall surface. The computational analysis reveals that use of hydrophobization admixtures in the gypsum element does not lead to any improvement of hygrothermal behavior of the envelope provided by an exterior thermal insulation. Therefore, the application of a gypsum element without any hydrophobization seems to be a more favorable solution. The common hydrophobized thermal insulation materials on the basis of polystyrene or mineral wool are found to be satisfactory from the point of view of hygrothermal performance of the analyzed cast-gypsum based envelope.

Keywords: building envelope, flue gas desulphurization (FGD) gypsum, thermal insulation boards, heat and moisture transport.

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1 Introduction

Calcined gypsum is a historical binder, which was, used already several thousands years ago. Gypsum was called gatch in Persia, gypsos in Greek, and gypsum in Latin. Iranians, Egyptians, Babylonians, Greeks, and Romans were familiar with the art of working with gypsum plasters; decorated interior walls were found for instance in Pompeii. Gypsum was found in the binder of buildings in the territory of today's Syria dated 7000 B.C.; it was also used in Cheops pyramid 2650 B.C, in the palace of Knossos etc. Nowadays, calcined gypsum is used in many technological modifications, which should improve its properties, in particular as binder of rendering mortars, for the production of stuccowork and also for plasters [1].

In the second half of the 20th century, new technologies for desulfurization of flue gases in power stations and heating plants appeared which were based on the reaction of sulfur (II) oxide formed during combustion of brown coal with high content of sulfur with limestone. Although these technologies were definitely very suitable from the point of view of the protection of environment, one problem appeared from the very beginnings, namely the very high amount of flue gas desulfurization (FGD) gypsum as waste product.

The utilization of FGD gypsum as secondary raw material remained insufficient considering the amount of its production until these days. For instance, in Czech Republic calcined gypsum is produced from FGD gypsum only in one power station (Počerady), the remaining production ends with gypsum that is used only partially as additive retarding the setting of cement. Calcined gypsum is mostly used for the production of gypsum plasterboards [2]. That part of produced gypsum, which is not utilized, is deposited as waste. However, FGD gypsum can be potentially used as a material for load bearing structures as well. Modifications of this material can enhance its original properties and increase its service life. In this paper, a computational assessment of hygrothermal performance of a building envelope based on several modifications of FGD gypsum is done.

2 Materials and building envelopes

In the computer simulations of temperature and relative humidity fields we have solved three variations of FGD gypsum wall, based on the raw material and on two types of hydrophobized gypsum, with the thickness of 300 mm (Fig. 1). The thermal insulation function of the wall was achieved by exterior thermal insulation boards with the thickness of 100 mm, which were considered in four variants. Insulation I was hydrophilic material with low value of hygroscopic moisture content on mineral wool basis, Insulation II capillary active material with higher value of hygroscopic moisture content on calcium-silicate basis, Insulation III hydrophobic material with low value of water vapor resistance factor on mineral wool basis and Insulation IV hydrophobic material with higher value of water vapor resistance factor on polystyrene basis. On the external side of the wall, lime plaster with the thickness of 10 mm was used.

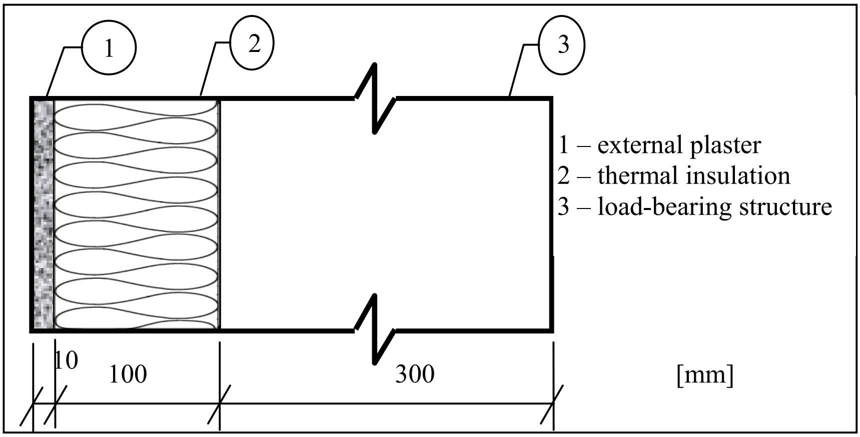

Figure 1: Composition of building envelope used to computer simulation.

The basic FGD gypsum material (we will denote it S0 in what follows) was β-form of calcined gypsum with purity higher than 98% of FGD gypsum, produced at the electric power station Počerady, CZ. The water/gypsum ratio was 0.627. After classification according to the Czech standard ČSN 72 2301, the gypsum was categorized as G-13 B III [3]. The first modification of FGD gypsum (S3) contained the admixture IMESTA IBS 47 produced by Imesta Inc., Dubá u České Lípy, CZ. The other (S4) contained the admixture ZONYL 9027 produced by Du Pont, USA. The water/gypsum ratio was the same as for S0. The composition of gypsum materials is shown in Table 1.

Table 1: Composition of gypsum materials.

Material	Water/gypsum ratio	Admixture	Concentration of the admixture
S0	0.627	none	none
S3	0.627	IMESTA IBS 47	0.5% by mass
S4	0.627	ZONYL 9027	5.0% solution

The material properties of non-modified and modified gypsum were measured in the Laboratory of Transport Processes (LTP), Faculty of Civil Engineering, Czech Technical University in Prague [4]. They are given in Table 2, where ρ is the bulk density, c the specific heat capacity, κ the moisture diffusivity, μ the water vapor diffusion resistance factor, θ_{sat} the saturated moisture content, θ_{hyg} the maximum hygroscopic moisture content, λ the thermal conductivity. The properties of insulation materials and lime plaster were partially obtained from the material database of Delphin computer code [5] and partially measured in LTP. The material properties of insulation boards are given in Table 3.

Table 2: Basic materials properties of gypsum.

	ρ	c	κ	μ	θ_{sat}	θ_{hyg}	λ
	[kg/m^3]	[J/kgK]	[m^2/s]	[-]	[m^3/m^3]	[m^3/m^3]	[W/mK]
S0	1019	840	2.63e-7	5.4	0.6	0.23	0.47
S3	942	840	1.47e-7	5.4	0.61	0.181	0.41
S4	941	840	7.32e-9	5.4	0.62	0.166	0.38

Table 3: Material parameters of insulation materials.

	ρ	c	κ	μ	θ_{sat}	θ_{hyg}	λ
	[kg/m^3]	[J/kgK]	[m^2/s]	[-]	[m^3/m^3]	[m^3/m^3]	[W/mK]
I	150	840	$1 \cdot 10^{-7} \cdot e^{0.0485 \cdot \theta}$	2	0.95	0.006	1.1
II	230	1000	$2 \cdot 10^{-8} \cdot e^{0.0523 \cdot \theta}$	2.5	0.88	0.22	0.4
III	280	840	$5 \cdot 10^{-13} \cdot e^{0.1486 \cdot \theta}$	3	0.31	0.0073	1.2
IV	30	1300	$2 \cdot 10^{-11} \cdot e^{0.0475 \cdot \theta}$	50	0.97	0.001	0.56

3 Numerical solution by TRANSMAT

For the calculations we employed the computer simulation tool TRANSMAT 4.3 [6] which was developed in the Department of Mechanics, Faculty of Civil Engineering, Czech Technical University in Prague. The construction of the code is based on the application of the general finite element computer simulation tool SIFEL (SImple Finite ELements) developed in the Department of Mechanics, FCE CTU. The moisture (1) and heat balance (2) equations were formulated according to the Künzel's model [7],

$$\frac{d\rho_v}{d\varphi}\frac{\partial\varphi}{\partial t} = div\left[D_\varphi grad\varphi + \delta_p grad(\varphi p_s)\right] \tag{1}$$

$$\frac{dH}{dT}\frac{\partial T}{\partial t} = div(\lambda gradT) + L_v div\left[\delta_p grad(\varphi p_s)\right] \tag{2}$$

where ρ_v is partial moisture density, φ the relative humidity, δ_p the water vapor permeability, p_s the partial pressure of saturated water vapor in the air, H the enthalpy density, L_v the latent heat of evaporation of water, λ the thermal conductivity and T is the temperature. The liquid water transport coefficient is defined as

$$D_\varphi = \kappa \frac{d\rho_v}{d\varphi}\,. \tag{3}$$

The proper initial and boundary conditions of the model are crucial factor affecting the reliability of the calculations. In our computer simulations, the analyzed building envelopes were exposed from inside to constant conditions (temperature equal to 21°C and relative humidity equal to 55%) and from outside to the climatic conditions corresponding to the reference year for Prague. The 1st of July was chosen as the starting point in the calculations.

We have chosen two characteristic profiles in the assessment of the hygrothermal performance of the envelope, A-A′, B-B′ (Fig. 2), where the profile A-A′ was between the insulation board and the load-bearing structure (the distance of 110 mm from the exterior), the profile B-B′ was the cross section of the wall from the exterior to the interior. In these profiles we have compared relative humidity and temperature calculated for the analyzed envelopes.

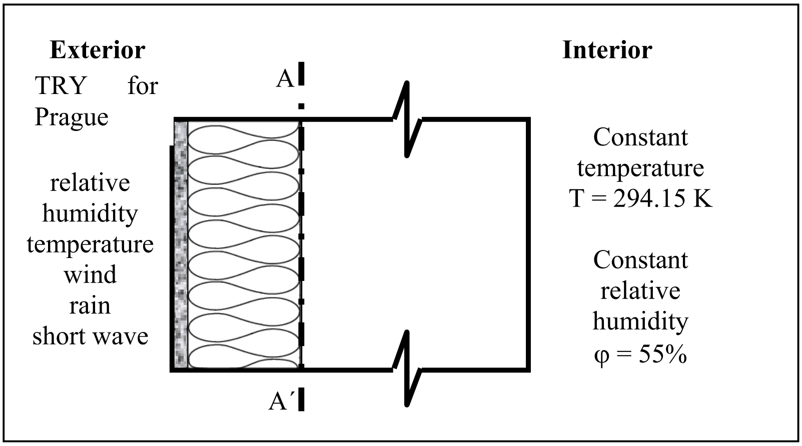

Figure 2: Scheme of typical envelope.

4 Computational results and discussion

4.1 Non modified gypsum S0

Fig. 3 shows an example of the relative humidity profile in the wall based on non-modified gypsum (S0) for December 15, which can be considered as characteristic for the winter period.

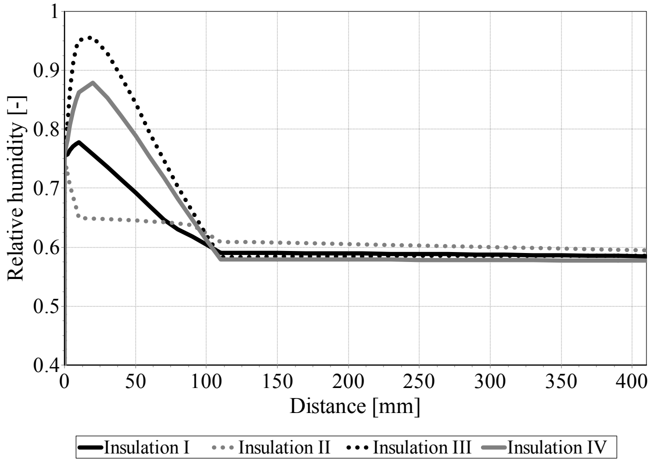

Figure 3: Relative humidity, non modified gypsum (S0), B-B′ profile.

Fig. 4 presents the history of relative humidity in the A-A′ profile from January 1 to December 31 for four years simulation.

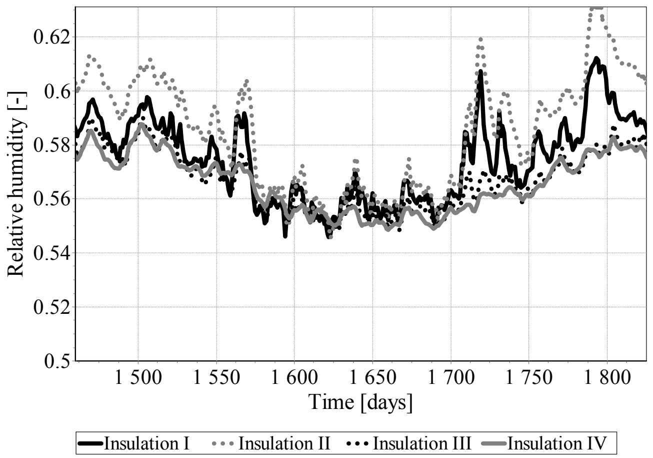

Figure 4: Relative humidity, non modified gypsum (S0), A-A′ profile.

Fig. 5 shows an example of the temperature profile in the wall based on the non-modified gypsum (S0) for December 15, which can be considered as characteristic for the winter period.

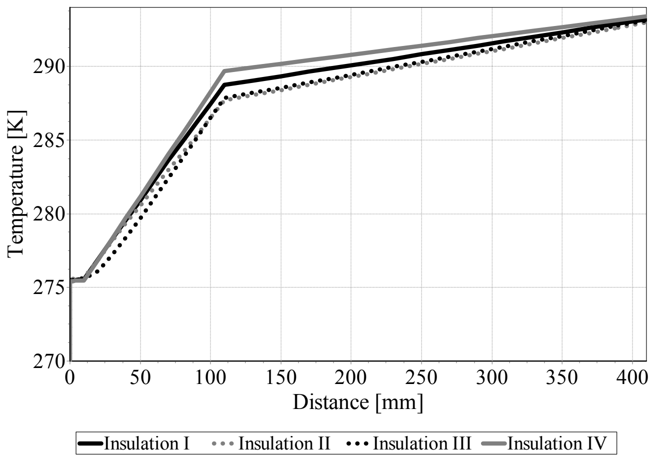

Figure 5: Temperature, non modified gypsum (S0), B-B´ profile.

4.2 Modified gypsum S3

Fig. 6 shows an example of the relative humidity profile in the wall based on the modified gypsum (S3) for December 15 analogous to Fig. 3. The results obtained for modified gypsum (S3) and non-modified gypsum (S0) were very similar, so that the effect of gypsum hydrofobization was very small. The same similar results were also achieved in the analogs to Figs. 4 and 5.

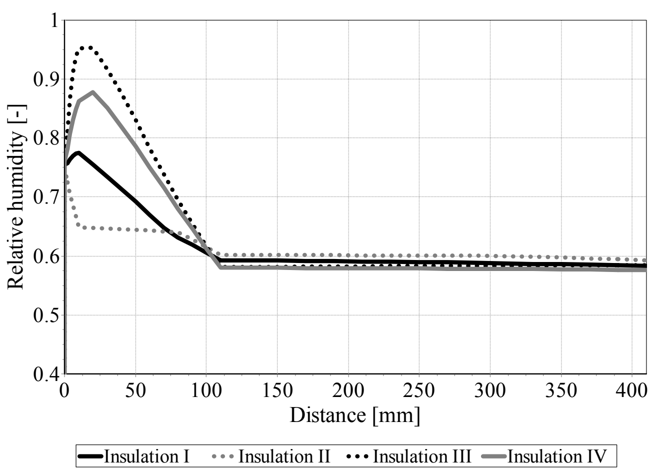

Figure 6: Relative humidity, modified gypsum (S3), B-B´ profile.

4.3 Modified gypsum S4

Fig. 7 shows an example of the relative humidity profile in the wall based on the modified gypsum (S4) for December 15. Here, some differences in relative humidity (mainly in the insulation layer and partially also in the gypsum element, the highest for Insulation II) compared to the results for S0 in Fig. 3 were observed but they were not very significant because they did not change the overall character of the hygrothermal performance of the gypsum wall.

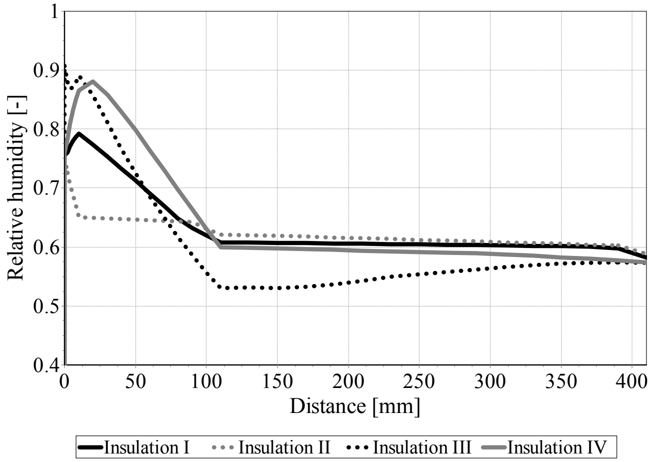

Figure 7: Relative humidity, modified gypsum (S4), B-B´ profile.

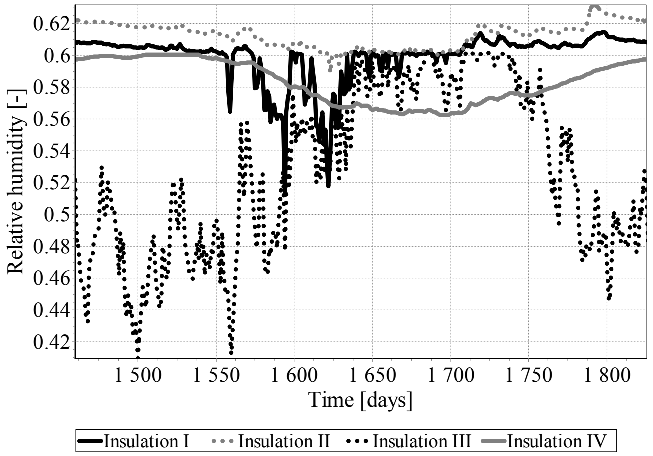

Figure 8: Relative humidity, modified gypsum (S4), A-A´ profile.

Fig. 8 presents the relative humidity history in the A-A´ profile from January 1 to December 31 for four years simulation. The differences observed in comparison with Fig. 4 for non-modified gypsum wall were most pronounced for

Insulation II similarly as in Fig. 7 but in the assessment of the overall hygrothermal performance of the wall, also here they could not be considered as very significant.

Fig. 9 shows an example of the temperature profile in the wall based on the modified gypsum (S4) for December 15. A comparison with the corresponding Fig. 5 reveals that the differences from the temperature profiles in the wall based on non-modified gypsum were almost negligible.

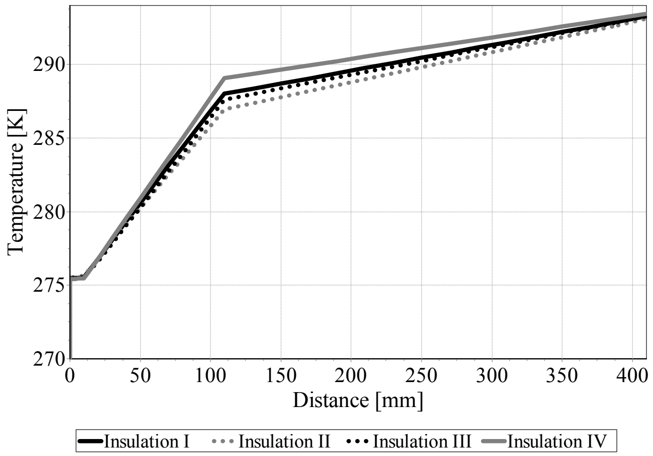

Figure 9: Temperature, modified gypsum (S4), B-B′ profile.

5 Conclusions

The computational analysis in this paper revealed that the use of hydrophobization admixtures in the cast-gypsum element of building envelopes provided by any of the four very different exterior thermal insulations did not lead to significant improvements of the hygrothermal behavior of the envelope. The hygrothermal performance of the studied envelopes was satisfactory in all analyzed cases. Therefore, an application of a gypsum element without any hydrophobization seems to be the preferential solution, particularly taking into account the substantially lower price. The common hydrophobized thermal insulation materials on the basis of polystyrene or mineral wool were found to be satisfactory from the point of view of hygrothermal performance of the analyzed cast-gypsum based envelope. Therefore, they are supposed to be the preferred materials in this respect.

Acknowledgements

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