Influence of characteristic types of thermal insulation on energy savings of AAC-based building envelope: a comparison

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Abstract

The energy efficiency calculations of several types of AAC-based building envelopes are presented in this paper. As boundary conditions, four different climates of Czech cities are chosen. The calculations are accomplished using Künzel's mathematical model of coupled heat and moisture transport implemented into computer simulation tool HEMOT. The main objective of this paper is to choose the best insulating material in order to reach maximal energy savings.
Keywords: AAC, energy efficiency, heat and moisture transport, computational simulation.

1 Introduction

Efforts to save energy nowadays have become evident in all the sectors of industry, in the building industry as well. The main reason for this fact is the permanent increase of energy prices, exhaustibility of traditional energy sources and the negative influence on the environment during their extraction.

Almost 40% of energy in EU is consumed in buildings; 57% of this amount on average is heating energy [1, 2]. That means, almost one quarter of overall energy consumption is allotted to heating. So there is a lot of space where energy could be saved. One of the possibilities in how to reach this objective is to use more effective heating systems, build low energy houses or improve the thermal capabilities of the envelopes of old buildings. This is also the main subject of a new EU directive known as EPBD II (Energy Performance of Buildings Directive II) [3], which orders the obligation of construction of "near zero energy

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houses” no later than 2021. This directive has to be implemented into national thermal standards. In the Czech Republic, thermal standard CSN EN 73 0540 – 2: Thermal protection of buildings – Part 2: Requirements [4] was already modified in 2011 in order to meet the new requirements. Among the others, the overall U-value of building envelope should be between 0.12 and 0.18 W/m^{2}K.

To reach these values it will be necessary to use new materials with excellent thermal insulating properties or use sufficient thickness of thermal insulation. One of prospective materials is, among others, autoclaved aerated concrete (AAC). The value of thermal conductivity is about 0.1 W/mK [5, 6] or higher depending on moisture content, however the extensive research is there still running in order to improve not only thermal but also hygric and mechanical parameters using for the most part, waste products [7–12]. These modified materials could be used in single-layer masonry as far as they meet thermal requirements or better recommendations. But this will be very difficult so it can be assumed, the presence of thermal insulation will be still necessary.

In this paper the effect of several types of thermal insulation on energy savings of AAC-based building envelope under different climatic conditions is compared.

2 Computational analysis

The computer code HEMOT [13] is based on the general finite element package SIFEL [14]. As basic input parameters of the mathematical model, hygric, thermal and basic physical parameters of used materials, scheme of construction detail, initial and boundary conditions and time specification of simulation are required. Description of all input parameters in more detail is given later.

In the computer simulations we focused on a comparison of energy efficiency of several building envelopes based on AAC provided with different thermal insulating materials.

2.1 Mathematical model

Künzel’s mathematical model of heat and moisture transport [15] was used in the simulations which can be formulated as

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

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

where ρ_v is the partial density of moisture, φ relative humidity, δ_p permeability of water vapour, p_s partial pressure of saturated water vapour, H enthalpy density, L_v heat of evaporation of water, λ thermal conductivity and T temperature,

$$D_\varphi = D_w \frac{d\rho_v}{d\varphi} \tag{3}$$

is liquid moisture diffusivity coefficient, D_w capillary transport coefficient.

2.2 Scheme of construction detail

Five variations of building envelope based on AAC were chosen for simulation. As a start-up building envelope we chose AAC without any thermal insulation, only with external and internal finishes which allowed us to get real image about energy efficiency of simple AAC building envelope (marked as I). In the next simulations we provided AAC with hydrophilic mineral wool (II), hydrophobic mineral wool (III), expanded polystyrene (IV) and Multipor Ytong produced by Xella CZ (V). All these envelopes were provided from interior and exterior side with Baumit MVR Uni plaster which is recommended for AAC structures as external finish. On the material interface between mineral wool and AAC an adhesive mortar layer was placed. Description of used materials in more detail is given in next subsection. Scheme of construction detail including the dimensions of each layer is shown in Figure 1.

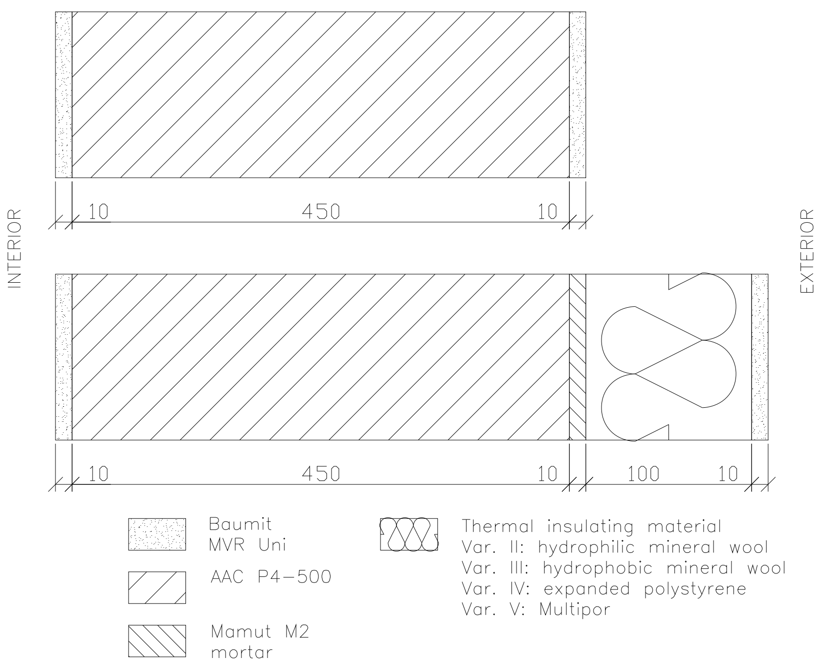

Figure 1: Scheme of AAC-based building envelope.

2.3 Material parameters

Autoclaved aerated concrete P4-500 produced by Xella CZ was under consideration in this paper as the load-bearing material. For exterior and interior renders we used Baumit MVR Uni Plaster, which is single-layer plaster for exterior and interior surfaces especially recommended for AAC. As the thermal insulation we assumed Rockwool hydrophilic mineral wool, hydrophobic mineral wool, expanded polystyrene and Multipor. For adhesive layer between AAC and mineral wool we used Mamut M2 mortar.

All the material parameters were measured in laboratory of transport processes at the Department of Materials Engineering and Chemistry, Faculty of Civil Engineering, Czech Technical University in Prague [16–18] and are summarized in Tables 1 and 2. We used these symbols: ρ – bulk density [kg/m^3], ρ_{mat} – matrix density [kg/m^3], ψ – porosity [%], c – specific heat capacity [J/kgK], μ – water vapour diffusion resistance factor [-], w – moisture content by volume [m^3/m^3], λ – thermal conductivity [W/mK], κ_{app} - moisture diffusivity [m^2/s].

Table 1: Material characteristics – Part I.

Parameter	AAC P4-500	Mamut M2 mortar	Baumit MVR Uni plaster
ρ [kg m^{-3}]	500	1430	1402
ψ [%]	80.2	42.6	44.4
c [J kg^{-1} K^{-1}]	1020 – 1510	1020	1020 - 1780
μ [-]	3.0 – 9.7	12.4	4.5 – 12.4
λ_{dry} [W m^{-1} K^{-1}]	0.114	0.481	0.443
λ_{sat} [W m^{-1} K^{-1}]	0.454	2.022	1.380
κ_{app} [m^2 s^{-1}]	5.82e-8	1.07e-9	1.59e-9
w_{hyg} [m^3 m^{-3}]	0.01846	0.0201	0.042

Table 2: Material characteristics – Part II.

Parameter	Hydrophilic mineral wool	Hydrophobic mineral wool	Expanded polystyrene	Multipor
ρ [kg m^{-3}]	71	270	50	125
ψ [%]	96.0	88.0	97.0	94.2
c [J kg^{-1} K^{-1}]	810	630	1300	2230 – 3500
μ [-]	4.3	3.0	50	1.9 – 10.9
λ_{dry} [W m^{-1} K^{-1}]	0.043	0.045	0.040	0.047
λ_{sat} [W m^{-1} K^{-1}]	0.246	0.246	0.560	0.166
κ_{app} [m^2 s^{-1}]	8.4e-6	2.51e-10	2.10e-11	3.26e-9
w_{hyg} [m^3 m^{-3}]	0.000046	0.0073	0.001	0.0078

2.4 Initial and boundary conditions and time interval of simulation

As the initial and boundary conditions (Figure 2) climatic data in the exterior in the form of Test Reference Year (TRY) for Prague, Liberec, Brno and Hradec Kralove were used. TRY contains average data for 30 years of temperature, relative humidity, rain, wind velocity and direction and solar radiation. On the interior side constant value of relative humidity 55% and temperature 21°C (see Fig. 2) was chosen. The simulation took 4 years in order to reach hygrothermal steady-state. The results are related to the last year.

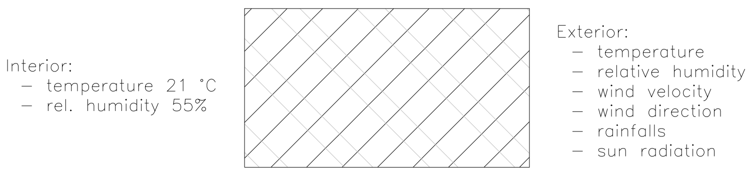

Figure 2: Boundary conditions.

2.5 Energy efficiency calculations

When the energy efficiency is evaluated, the results obtained in fifth year of simulation are taken into account. At first, the heat fluxes in boundary elements of building envelope cross-section are calculated according to the relation

$$q = -\lambda \frac{dT}{dx} \tag{4}$$

where q denotes the heat flux [W/m$^2_{\text{envelope}}$], λ is thermal conductivity depending on moisture content [W/mK], dT is difference between temperatures of two nodes defining the element [K] and dx is size of the element [m].

The value of thermal conductivity is determined from calculated moisture content according to the linear function characterized by values of λ_{dry} and λ_{sat} in Table 1 of Baumit MVR Uni plaster.

The energy efficiency per annum can be then calculated as integral of time function of heat flux according to the relation

$$Q = \int_{1Jan}^{31Dec} q(t)dt, \tag{5}$$

where Q denotes the energy efficiency per annum [kWh/m$^2_{\text{envelope}}$a] and $q(t)$ is time function of heat flux [W/m$^2_{\text{envelope}}$].

3 Computational results

The energy efficiency of presented building envelopes was calculated on the interior side because of more steady values of heat fluxes which are not affected

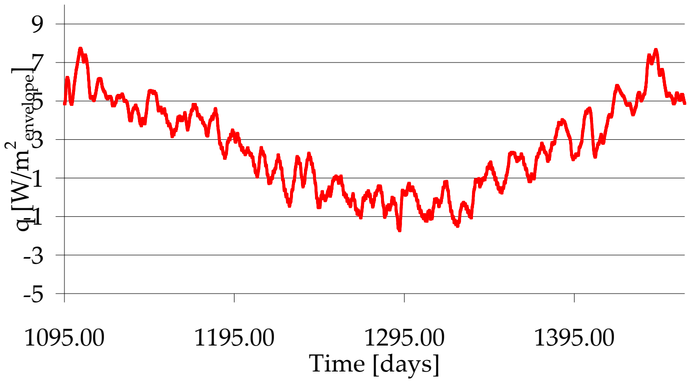

Figure 3: Heat flux on interior side, Brno, without thermal insulation.

by climatic conditions as much as on the exterior side. The evaluation has been accomplished in the fifth year of simulation (1095st – 1460th day).

Figures 3–7 show hourly values of heat flux on interior side of several building envelope. The figures are very similar so only the representatives are chosen. Figure 3 shows the hourly values of heat flux on interior side of building envelope without any insulation under Brno's climatic conditions, Figure 4 shows values of heat flux of building envelope provided with hydrophilic mineral wool under Prague's climatic condition. Figure 5 shows values of heat flux of building envelope provided with hydrophobic mineral wool under Hradec Kralove's climatic condition, Figure 6 shows values of heat flux of building envelope provided with expanded polystyrene under Liberec' climatic condition and Figure 7 shows values of heat flux of building envelope provided with Multipor under climatic condition of Prague.

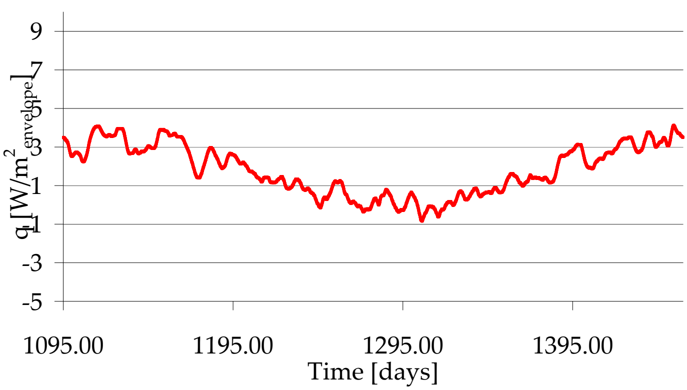

Figure 4: Heat flux on interior side, Prague, hydrophilic mineral wool.

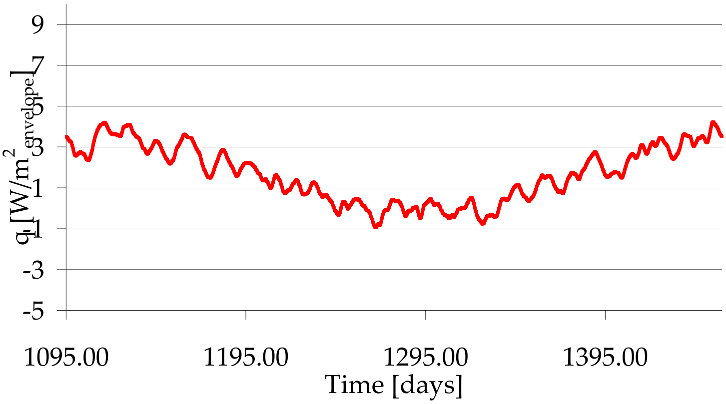

Figure 5: Heat flux on interior side, Hradec Kralove, hydrophobic mineral wool.

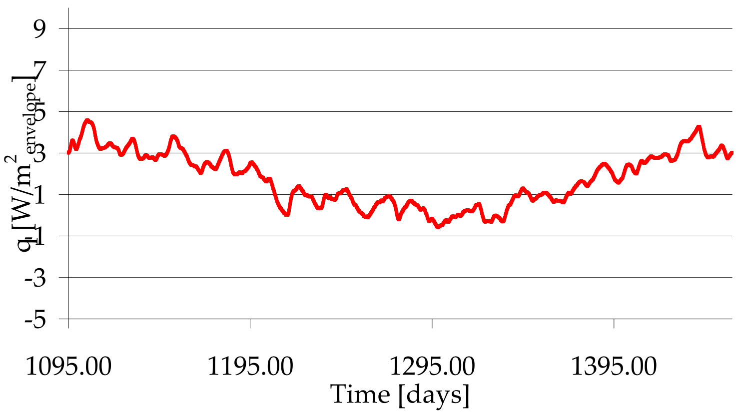

Figure 6: Heat flux on interior side, Liberec, expanded polystyrene.

When the heat fluxes were calculated, the values of thermal conductivity on interior side depending on moisture content were used. These values differ only a bit because the moisture content on the interior side is almost stable. Figure 8 shows values of thermal conductivity on interior side of building envelope provided with hydrophobic mineral wool. Figure 9 shows values of thermal conductivity on interior side under Prague's climatic conditions.

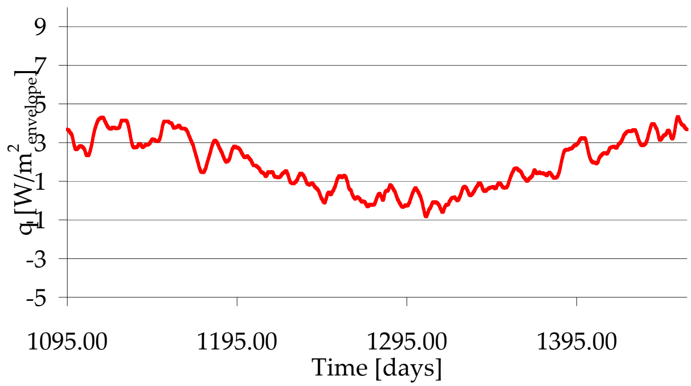

Figure 7: Heat flux on interior side, Prague, Multipor.

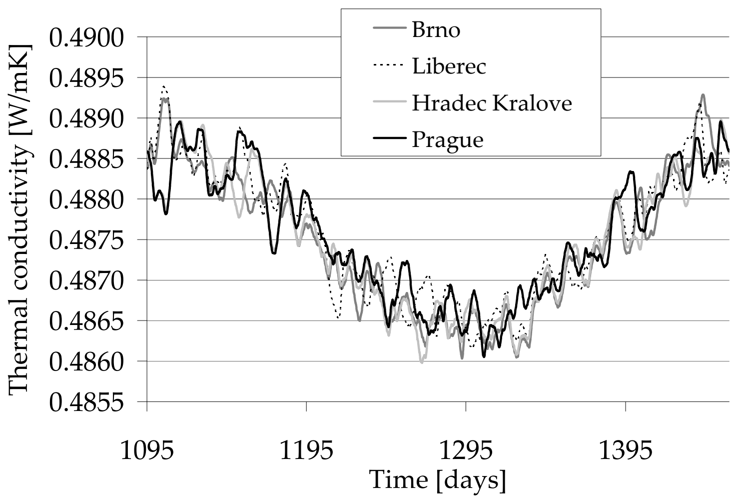

Figure 8: Values of thermal conductivity of building envelopes provided with hydrophobic mineral wool.

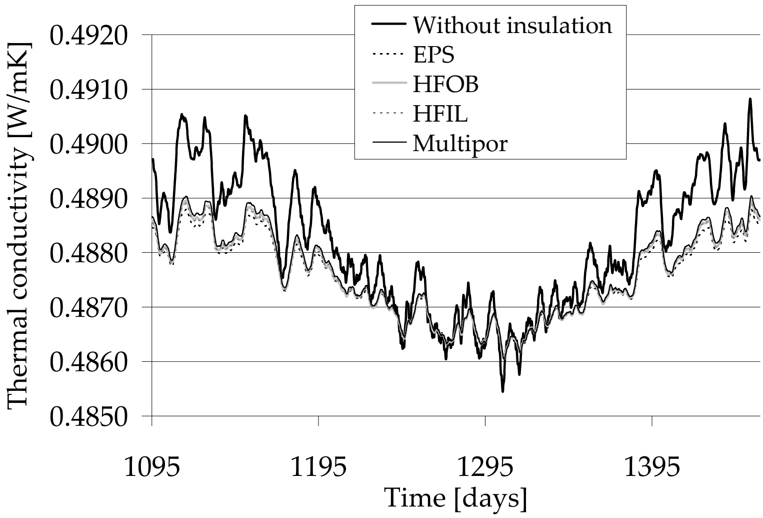

Figure 9: Values of thermal conductivity of building envelopes under Prague's climatic conditions.

The energy efficiency per annum given by integral of time function of heat flux is summarized in Table 3. We obtained two values, on interior and exterior side. Because the calculations were accomplished in non-steady state, these values are different. This is caused by heat accumulation inside the building envelope. As the decisive values we assumed the results on interior side which is not as affected by hourly climatic changes as the exterior side.

Table 3: Energy efficiency results [$kWh/m^2_{envelope}a$].

	Brno	Hradec Kralove	Liberec	Prague
Without thermal insulation	22.715	22.813	25.150	24.900
Expanded polystyrene	13.699	13.786	15.198	15.046
Hydrophobic mineral wool	14.470	14.558	16.044	15.895
Hydrophilic mineral wool	14.353	14.443	15.933	15.782
Multipor	15.018	15.097	16.642	16.486

4 Discussion

The results presented in this paper show that energy efficiency of building envelope depends on its composition and on climatic conditions which it is exposed to.

Within the frame of this research, four different towns have been chosen, namely Prague, Brno, Liberec and Hradec Kralove, which have different position and altitude. The relatively worst climatic conditions have Prague and Liberec, which was confirmed comparing energy balance of identical building envelopes.

Whereas the thermal properties within the investigated insulating materials are almost identical in dry state, the moisture transport parameters differ significantly. Therefore the differences in energy efficiency can be expected. For instance, if moisture diffusivity is compared, it can be noticed, hydrophilic mineral wool differs almost up to 5 orders of magnitude from other thermal insulations and liquid moisture transport is then much faster. Furthermore, water vapor diffusion resistance factor of expanded polystyrene is up to 30 times higher than hydrophobic mineral wool and up to 25 times higher than hydrophilic mineral wool. It means, both types of mineral wool are easily vapor-permeable. This leads to increase of their moisture content and decrease of thermal insulating properties. However, it allows the construction to "breathe." As a result, the moisture accumulation from interior due to usage of building inside the envelope is eliminated. It is very important because of elimination of biological or mechanical corrosion. On the other hand, the certain forfeit for this is a slight increase of energy demand of building.

According to the results, expanded polystyrene seems to be the best thermal insulating material as it reduces the heating costs in comparison with non-insulated building envelope averagely by 39.6%. Multipor reduced heating costs only by 33.8%, hydrophobic mineral wool by 36.2% and hydrophilic mineral wool by 36.7%.

It can be summarized from a point of view of energy savings that expanded polystyrene is the most advantageous material to be used in order to save the energy and environment as well. However, the extensive research of AAC based building envelopes proves, that hydrophilic mineral wool is one of the most considerate among the common insulating materials to applied external finish and positively affects the service life of the whole envelope [19].

5 Conclusions

In this paper, the energy efficiency of several types of building envelopes under different climatic conditions has been analyzed. The envelope consisted of AAC provided with four different types of thermal insulation, namely expanded polystyrene, hydrophobic and hydrophilic mineral wool and Multipor. Climatic conditions of Brno, Hradec Kralove, Liberec and Prague were assumed.

All the results presented in this paper were obtained using computational-experimental approach of coupled heat and moisture transport. In comparison with Czech standards is this method more advantageous because presence of moisture content is not neglected and the results are then more accurate.

It was shown that the best choice from point of view of energy savings is expanded polystyrene, because it will reduce the heating costs by almost 40%. However, it is important to realize, the energy efficiency is not the only single factor playing a role during the building envelope design. It is important to also take into consideration other factors such as durability. Otherwise the repair costs may exceed the costs saved on heating.

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