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Effect of Environmental Conditions on Energy Efficiency of AAC-based Building Envelopes

V. Koci, J. Madera and R. Cerny

Abstract**—**Calculations of energy efficiency of several AAC-based building envelopes under different climatic conditions are presented. As thermal insulating materials, expanded polystyrene and hydrophobic and hydrophilic mineral wools are assumed. The computations are accomplished using computer code HEMOT developed at Department of Materials Engineering, Faculty of Civil Engineering at the Czech Technical University in Prague. The climatic data of Athens, Kazan, Oslo, Prague and Reykjavík are obtained using METEONORM software.

Keywords**—**climatic conditions, computational simulation, energy efficiency, thermal insulation

I. Introduction

NOWADAYS, one of the current trends in building industry is the tendency to use new materials with still better thermal insulating properties in order to enhance the thermal insulating capabilities of building envelope. This can lead to significant financial savings as average value of heating energy consumption in EU is about 57% and in several countries even higher (e.g. in Poland 70%) [1 – 2].

One of the relatively new materials among others is aerated autoclaved concrete (AAC). Properties and durability of AAC very depend on its hygrothermal performance and properties of other layers which is whole building envelope consisting of. Value of thermal conductivity is 0.1 W/mK or higher [3 – 4] 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 instance bottom ash [5 – 6], silica fume [7] or some other waste products for the most part [8 – 10]. These modified materials can be used then in single-layer masonry without thermal insulation as far as they meet requirements or better recommendations of valid standards. The Czech standard ČSN EN 73 0540 – 2: Thermal protection of buildings – Part 2: Requirements [11] requires value of overall heat transfer coefficient (U-value) of 0.38 W/m^{2}K, however it recommends value of 0.25 W/m^{2}K, but without thermal insulation is this value hardly achievable. In addition, if we have a respect to more stringent requirements on thermal protection of buildings, the recommended U-value will be achievable only in assumption of unreal thickness of masonry. For instance, last updating from October 2010 of British standard L1A Conservation of fuel and power in new dwellings [12] requires U-value 0.25 W/m^{2}K. However, similar steps with even lower U-values (0.18 – 0.12 W/m^{2}K) can be expected around Europe due to implementation of EPBD II directive no later than 31.12.2020. That means in the future, the presence of thermal insulation in building envelopes might be unavoidable.

Thermal insulating systems can be basically sorted in two groups, external and internal, where the externals are much more common. However, its application is not always possible or advantageous. For example the preservation of historical buildings' facades is very often required so application of external thermal insulating system is excluded. Another sorting criterion is material of thermal insulation. The most common are expanded polystyrene and hydrophobic mineral wool, however also extruded polystyrene, hydrophilic mineral wool or calcium silicate have certain share on building market. Material parameters determine significant properties of insulation systems (water vapor diffusion, moisture diffusivity, thermal properties etc.) so it is necessary to chose wisely considering all factors such as climatic conditions or material of the wall.

We can judge the optimality of composition of building envelope from many points of view, e. g. from point of view of service life, mechanical properties or salt resistance. In this paper we focus on energy efficiency of building envelope under different climatic conditions given by several geographical locations around Europe and we try to determine the best thermal insulating material in order to reach the highest energy savings.

II. Computational Analysis

A. Mathematical Model

Künzel's mathematical model of heat and moisture transport [13] was used in the simulations which can be formulated as

V. Kočí is with the Department of Materials Engineering and Chemistry, Faculty of Civil Engineering, Czech Technical University in Prague, Prague, Czech Republic (phone: 00420-22435-5435; fax: 00420-22435-4446; e-mail: vaclav.koci.1@fsv.cvut.cz).
J. Maděra is with the Department of Materials Engineering and Chemistry, Faculty of Civil Engineering, Czech Technical University in Prague, Prague, Czech Republic (phone: 00420-22435-5435; fax: 00420-22435-4446; e-mail: madera@fsv.cvut.cz).
R. Černý is with the Department of Materials Engineering and Chemistry, Faculty of Civil Engineering, Czech Technical University in Prague, Prague, Czech Republic (phone: 00420-22435-5044; fax: 00420-22435-4446; e-mail: cernyr@fsv.cvut.cz).

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

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

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,

$$D_\varphi = D_w \frac{d\rho_v}{d\varphi} \quad (3)$$

is liquid moisture diffusivity coefficient, D_w capillary transport coefficient.

The computational analysis was accomplished by computer code HEMOT [14], which was developed at the Department of Material Engineering and Chemistry, Faculty of Civil Engineering, Czech Technical University in Prague on the basis of the general finite element package SIFEL [15].

B. Properties of Materials Involved in Building Envelope

In this paper, the load bearing wall made from AAC in thickness of 300 mm is under assumption. The wall is provided with external thermal insulation (hydrophobic mineral wool, hydrophilic mineral wool and expanded polystyrene) in thickness of 100 mm. There is also 10 mm thick adhesive layer between AAC and thermal insulation. We assumed external and internal finishes in thickness of 10 mm from plaster developed especially for AAC constructions.

The values of material parameters were taken from [4, 16 – 18] and are summarized in Table I and II.

TABLE I
MATERIAL CHARACTERISTICS OF INVOLVED MATERIALS – PART 1

	AAC P2-400	Adhesive layer Mamut M2	Baumit MVR Uni
ρ [kg/m^3]	412	1430	1402
ψ [%]	80.3	42.6	44.4
c [J/kgK]	1250-1385	1020	1020-1780
μ [-]	3.7-14.4	12.4	4.5-12.4
λ_{dry} [W/mK]	0.094	0.481	0.443
λ_{sat} [W/mK]	0.434	2.022	1.380
κ_{av} [m^2/s]	1.12e-9	1.07e-9	1.59e-9
w_{hyg} [m^3/m^3]	0.019	0.015	0.042

TABLE II
MATERIAL CHARACTERISTICS OF INVOLVED MATERIALS – PART 2

	Expanded polystyrene	Hydrophobic mineral wool	Hydrophilic mineral wool
ρ [kg/m^3]	50	270	71
ψ [%]	97.0	88.0	96.6
c [J/kgK]	1300	630	810
μ [-]	50	2.1-3.7	1.5-3.2
λ_{dry} [W/mK]	0.040	0.045	0.043
λ_{sat} [W/mK]	0.560	0.246	0.751
κ_{av} [m^2/s]	2.10e-11	2.51e-10	8.4e-6
w_{hyg} [m^3/m^3]	0.001	0.007	0.00026

The following symbols were used: ρ – bulk density [kg/m^3], ψ – porosity [%], c – specific heat capacity [J/kgK], μ – water vapor diffusion resistance factor [-], λ_{dry} – thermal conductivity in dry conditions [W/mK], λ_{sat} – thermal conductivity in water saturated conditions [W/mK], κ - moisture diffusivity [m^2/s], w_{hyg} – hygroscopic moisture content by volume [m^3/m^3].

C. Initial and Boundary Conditions

Initial and boundary conditions should be as realistic as possible. This was the reason why we used climatic data in the exterior in the form of Test Reference Year for cities around Europe, namely Athens, Kazan, Prague, Oslo and Reykjavík, which contains long-term average data. They were obtained using Meteonorm software, version 6.1, which is meteorological database and computer program for climatological calculations for every location on the globe. On the interior side we used constant values of relative humidity 55% and temperature 21°C.

Athens has a subtropical Mediterranean climate. The dominant feature of Athens climate is alternation between prolonged warm and dry summers and mild, wet winters. With an average of 414.1 millimeters of yearly precipitation, rainfall occurs largely between the months of October and April. July and August are the driest months. Winters are cool and rainy, with a January average of 8.9 °C. Snowstorms are infrequent but can cause significant disruption when they occur. Snowfalls are more frequent in the northern suburbs of the city.

Kazan has a humid continental climate with long cold winters and warm, often hot dry summers. The warmest month is July with daily mean temperature near 20 °C, coldest - January −12 °C.

Oslo has a humid continental climate. Because of the city's northern latitude, daylight varies greatly, from more than 18 hours in midsummer, when it never gets completely dark at night, to around 6 hours in midwinter. Despite its northerly location, the climate is relatively mild throughout the year because of the Gulf Stream. Oslo has pleasantly mild to warm summers with average high temperatures of 20–22 °C and lows of around 12 °C. Winters are cold and snowy with temperatures between −7 °C up to −1 °C. Temperatures have tended to be higher in recent years. Annual precipitation is 763 millimeters with moderate rainfall throughout the year. Snowfall can occur from November to April, but snow accumulation occurs mainly from January through March.

Prague has borderline oceanic climate. The winters are relatively cold with very little amount of sunshine. Snow cover is common between mid-November to late March but is usually not too heavy. Summers usually bring fine sunny days with highs being around 25 degrees. Nights can be quite cool even in summer, though. Precipitation in Prague is rather low as the shadow of the Ore Mountains and the Czech Central Highlands takes effect. The driest season is usually winter while the summers can bring quite heavy rain especially in form of violent storms and showers.

Reykjavík's temperatures very rarely drop below −15 °C in the winter. This is because the Icelandic coastal weather in winter is moderated by the warm waters of the Gulf Stream. The climate is subpolar oceanic, and the city is on the northern edge of the temperate zone. Summers are cool, with temperature fluctuating between 10 to 15 °C, sometimes exceeding 20 °C. Reykjavík is not a particularly wet city, but it nevertheless averages 148 days with measurable precipitation every year. Spring tends to be the sunniest season, May particularly. Annual sunshine hours in Reykjavík are around 1,300, which is comparable with other places in Northern and North-Eastern Europe. The highest ever recorded temperature in Reykjavík was 26.2 °C, while the lowest ever recorded temperature was −24.5 °C.

For illustration, daily temperatures in Kazan and Athens are captured in Figure 1, relative humidity in Prague and Reykjavík is captured in Figure 2.

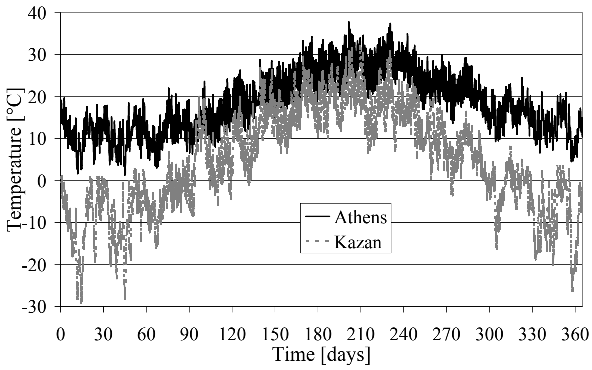

Fig. 1 Daily temperature in Athens and Kazan

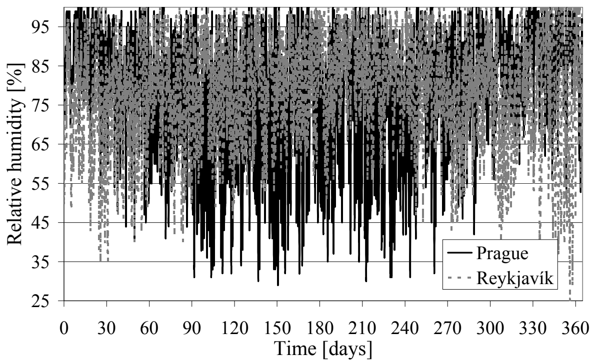

Fig. 2 Daily relative humidity in Prague and Reykjavík

D.Energy Efficiency Calculations

When the energy efficiency is evaluated, the results obtained in third 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

$$q = -\lambda \frac{dT}{dx}, \quad (4)$$

where q denotes the heat flux [$W/m^2_{envelope}$], 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 I 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

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

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

III. Computational Results

The energy efficiency of studied building envelopes was calculated on the interior side because of more steady values of heat fluxes which are not affected by climatic conditions as much as on exterior side. The evaluation has been accomplished in third year of simulation (730[th] – 1095[th] day).

Figures 3 – 7 show hourly values of heat flux on interior side of 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 provided with EPS under Athens' climatic conditions, Figure 4 shows values of heat flux of building envelope provided with hydrophilic mineral wool under Kazan's climatic condition.

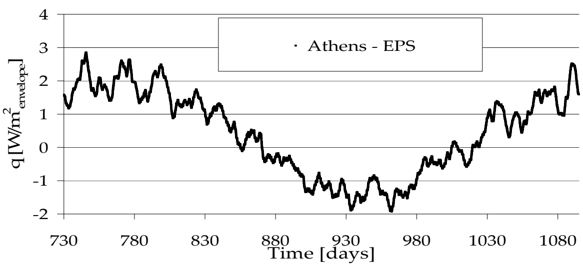

Fig. 3 Heat flux on interior side, Athens, expanded polystyrene

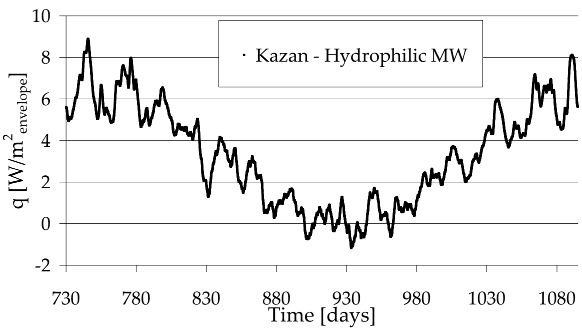

Fig. 4 Heat flux on interior side, Kazan, hydrophilic mineral wool

Figure 5 shows values of heat flux of building envelope provided with hydrophobic mineral wool under Prague's climatic condition, Figure 6 shows values of heat flux of building envelope provided with expanded polystyrene under Oslo's climatic condition and Figure 7 shows values of heat flux of building envelope provided with hydrophilic mineral wool under Reykjavík's climatic condition.

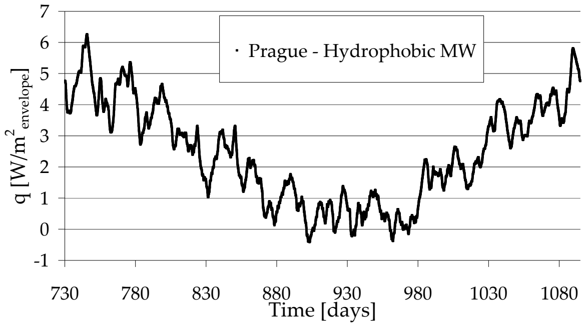

Fig. 5 Heat flux on interior side, Prague, hydrophobic mineral wool

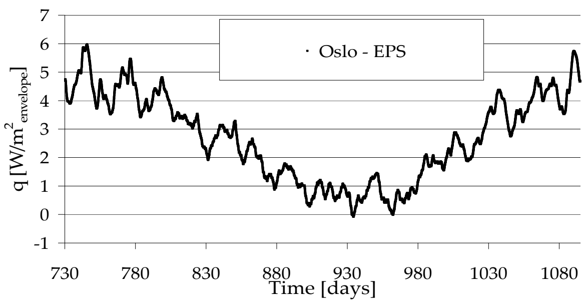

Fig. 6 Heat flux on interior side, Oslo, expanded polystyrene

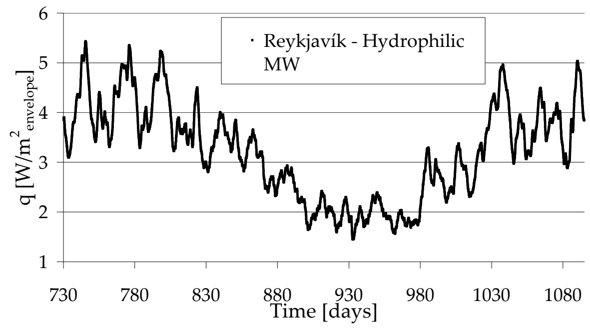

Fig. 7 Heat flux on interior side, Reykjavík, hydrophilic mineral wool

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 8-10 show values of thermal conductivity on interior side of building envelope provided with hydrophobic mineral wool (Fig. 8), hydrophilic mineral wool (Fig. 9) and EPS (Fig. 10).

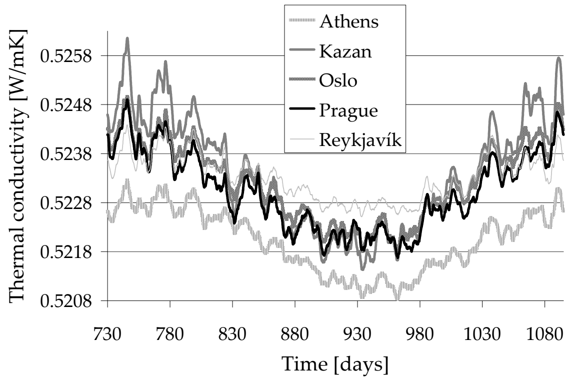

Fig. 8 Values of thermal conductivity on interior side of building envelope provided with expanded polystyrene

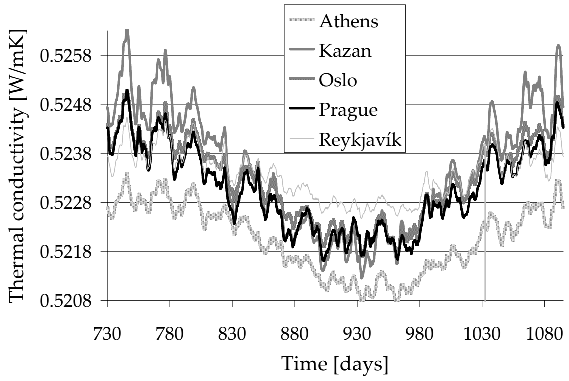

Fig. 9 Values of thermal conductivity on interior side of building envelope provided with hydrophobic mineral wool

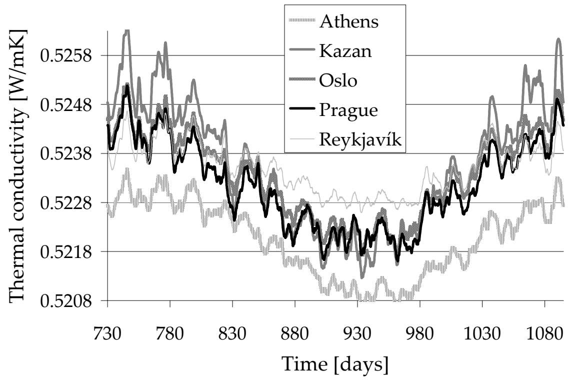

Fig. 10 Values of thermal conductivity on interior side of building envelope provided with hydrophilic mineral wool

The energy efficiency per annum given by integral of time function of heat flux is summarized in Table III. 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.

The plus sign of energy efficiency means the energy loss, it can be understood as the amount of heating energy necessary to keep constant values of temperature 21 °C in interior. On the other hand, the minus sign can be understood as the amount of energy consumption on cooling to keep the temperature at 21 °C.

TABLE III
ENERGY EFFICIENCY RESULTS (KWH/$M^2_{ENVELOPE}$)

	Expanded polystyrene	Hydrophobic mineral wool	Hydrophilic mineral wool
Athens	3.7	4.0	4.0
Kazan	26.5	28.0	29.2
Oslo	23.6	24.6	25.9
Prague	20.1	21.2	22.1
Reykjavík	25.1	26.6	28.0

IV. DISCUSSION

As the results presented in this paper show, the energy efficiency of thermal insulation is highly dependent on climatic conditions of given region. Whereas Athens and Reykjavík experience an oceanic climate, Kazan, Oslo and Prague have continental climate. The significant influence has not only the air temperature, but also the relative humidity in particular. It can be spoken in general, the regions with oceanic climate have more stringent requirements on thermal insulation than regions with continental climate. This is caused by relative humidity of air inside the porous body of materials of building envelope, which leads to increase of moisture content and to deterioration of thermal insulating properties. The efficiency of thermal insulation is under these climatic conditions determined by its moisture transport parameters.

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, especially under oceanic climatic conditions. For instance, if moisture diffusivity is compared, it can be noticed, hydrophilic mineral wool differs almost up to 5 orders of magnitude 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 slight increase of energy demand of building.

As it is obvious in Table III, hydrophilic mineral wool in comparison with expanded polystyrene raises the heating costs from 5.0 up to 8.1 %; in case of hydrophilic mineral wool, the heating costs in comparison with expanded polystyrene are raised little bit more (8.1 up to 11.6 %).

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 whole envelope [19].

V. 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 three different types of thermal insulation, namely EPS and hydrophobic and hydrophilic mineral wool. Climatic conditions of Athens, Kazan, Oslo, Prague and Reykjavík were assumed.

All the results were achieved using computational analysis of coupled heat and moisture transport which is more advantageous than assessment according to the standards, because the liquid moisture transport is not neglected and the results are then more accurate.

The results of this paper showed, best choice from point of view of energy efficiency is to choose expanded polystyrene. However, it is important to realize, the energy efficiency is not only single factor playing the role during the building envelope design. It is important to take into consideration also other factors such as durability. Otherwise the repair costs can strongly exceed the costs saved on heating.

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