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Investigation of Hydrothermal Performance of Fibrous Thermal Insulation Materials

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The hydrothermal performance of fibrous thermal insulation materials is dictated by the response of the system to combined heat, air and moisture fluctuations produced by exterior and interior conditions that exist on either side of the materials. This paper reports on experimental results to assess the drying and wetting rate of fibrous thermal insulation materials in close contact with various combinations of sheathing. Fibrous thermal insulation material, such as mineral wool, was used for investigation. Full-scale specimen of structure was installed in climatic chamber. A median divider separates the specimen in two equal areas: a specimen with sheathing and a specimen without sheathing (reference measurement). Both specimen sections were instrumented to allow direct comparison of the hydrothermal performance. Observations from the full-scale specimen showed that there is a risk moisture accumulation in wall structure, because the water vapour permeability of external layer of fibrous thermal insulation material plays the significant role. According to the results, the *R*-value decreased 15 % from initial level while moisture content of the external layer of mineral wool increased 10 %.

Keywords: hydrothermal performance, full-scale specimen, fibrous thermal insulation materials, water vapour permeability, external layer.

INTRODUCTION

The study of heat and mass transfers in building materials leads to a better understanding of hydrothermal behavior of structures in service conditions. The knowledge of material properties is necessary to predict the behaviour of buildings linked with their durability.

The walls are important parts of building enclosure in limiting heat losses, and they thus provide the conditions for a good indoor climate [1]. A thermal insulation materials such mineral wool, wind and vapour barriers have improved substantially the thermal insulation properties of the walls. Unfortunately it is quite difficult to evaluate this improvement when only thermal parameters of separate wall components are known [2]. The change of the hydrothermal properties of walls is especially difficult forecast due to changing environment conditions. On the external surface, the conditions are more or less severe due to temperature variation, solar radiation, wind, rain or other weathering conditions. On the internal surface, the temperature is usually regulated for the inhabitants' comfort. Therefore, the building components are exposed to two different climates which can create a hydrothermal and mechanical stresses and strains in the components. These stresses and strains can create damages that suffer the durability of the component. In multi-layered structures, there can be condensation that participate to deteriorate the components to a great extent [3].

In 1995 the research group of Vilnius Gediminas Technical University and Laboratory of Thermal Building Physics, Institute of Architecture and Construction initiated a research project investigating the hydrothermal performance of building partitions of wall structures. The aim of project was to produce documentation of wall with fibrous thermal insulation materials in Lithuanian climate conditions. There was a lack of data for design of thermal insulation in such structure.

During the first stage of experimentation, when heat transfer by conduction, radiation and convection, was determined and estimated the dependences of heat insulating properties of the building walls on the thermal physical properties of the thermal insulation materials and air movement in the thermo-insulating layers. The results from heat flow measurements were reported [4].

In this paper, we present some results of hydrothermal behavior of the fibrous thermal insulation materials, taking into account coupled heat and moisture transfer through the fibrous insulation layer.

METHODOLOGY

Heat and moisture transfer equations

During the last decades the coupled heat and moisture transfer in fibrous materials has been investigated by several researchers [5 – 7]. A lot models with different assumptions have been developed. It is well known, that in porous materials such as ceramic and concrete the main driving force for moisture transfer is the capillarity pressure. More complicated moisture migration mechanism is in a multi-layered wall structure, when fibrous materials are used. In these materials, water can be in solid, liquid or gaseous phase. In this case moisture is transferred not only by capillarity pressure, but due to diffusion as well as convection in vapor phase. Heat is transferred by radiation, conduction, convection and latent heat [8].

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In current research the numerical simulation method was employed [9]. This method is used for determination of hydrothermal performance of a structure that includes heat and moisture transfer in one dimension. If the flow directions shown in Fig. 1 are used, heat flux q and moisture flow g are as follows:

$$q=-\lambda\frac{\partial T}{\partial x};\quad g=-\delta_v\frac{\partial v}{\partial x}, \tag{1}$$

where λ is the thermal conductivity of the material; the vapor diffusion coefficient is denoted by δ_v; the humidity by volume in the surrounding air is denoted v (kg/m^3).

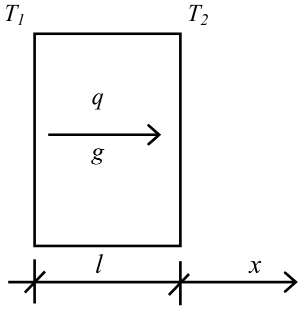

Fig. 1. Flow directions used in Eq. 1

The balance equations are:

$$-\frac{\partial}{\partial x}\left(-\lambda\frac{\partial T}{\partial x}\right)=\frac{\partial T}{\partial t};\quad -\frac{\partial}{\partial x}\left(-\delta_v\frac{\partial v}{\partial x}\right)=\frac{\partial w}{\partial t}, \tag{2}$$

where w – denotes the water content of the material considered.

Using the above-mentioned method, calculation was performed on common wall structure: unventilated masonry wall with mineral wool insulation. Table 1 shows the set of data used in the calculation. The outdoor temperature and relative humidity were taken for Kaunas city [10]; indoor temperature and relative humidity was +20 °C and 60 %, respectively. According to the results achieved during calculation, it has been determined that until coldest month (January) on internal surface of finishing layer moisture content increased to 389 g/m^2. In this case it would expect that U-value of structure increases while moisture content increases.

Table 1. Parameters of materials used in the simulation

Layer	S_d - value, m	R - value, m^2·K/W
Outdoor	–	0.04
External layer (sheathing)	1.5	0.15
Mineral wool	0.1	2.78
Internal layer (sheathing)	2.09	0.35
Indoor	–	0.13
Total value	3.69	3.45

The experimental investigation was performed in order to determine the effect of moisture content on heat transfer through the partitions in which the fibrous thermo-insulating materials are used.

Experimental set-up

The climatic chamber system consists of two climatic chambers (warm and cold) separated by a full-scale type specimen of measured material. Equipment was created for experimental analysis according to the requirements of the international standards ISO 8301 and ISO 8990. The density values of temperature and heat flow in the sample were measured under stationary environmental conditions, when the temperature and relative humidity (RH) of climatic chamber was:

- θ_i = +20 °C and RH = 55 % in warm chamber;
- θ_e = 0 °C, θ_e = −10 °C, RH = 80 % in cold chamber.

The organization of the whole measuring system is shown schematically in Fig. 2.

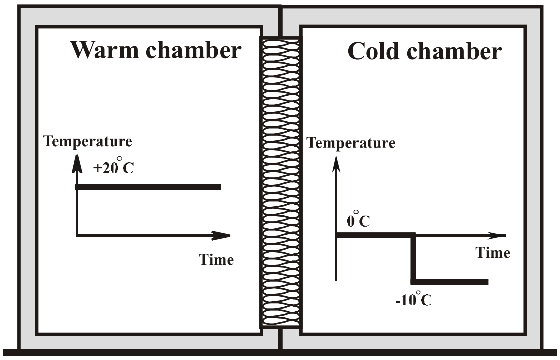

Fig. 2. The scheme of climatic chamber system

The test wall was mounted between cold and warm chambers. The height of the structure tested in this equipment was 1480 mm, the width was 1230 mm, and the thickness of fibrous material was 100 mm. A median divider separates the specimen in two equal areas: a specimen with external sheathing (case A) and a specimen without external sheathing – reference measurement (case B). This means that the drying out of moisture was analyzed using set-up where there is 1-dimensional moisture transport under constant temperature difference of adjacent air spaces. In the firs section (case A) water vapour could flow through the fibrous insulation and external sheathing while temperatures > 0 °C, but when the condensed water freezes at their surface, the real water permeance decreases strongly. In the next section (case B) external surface of fibrous material was without barrier. Both specimen sections were instrumented to allow direct comparison of the hydrothermal performance (Fig. 3).

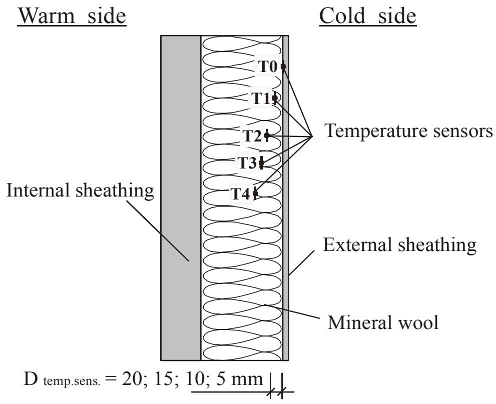

Fig. 3. Structure section (case A) and location of sensors

Thermal transmittance and thermal resistance of specimen were determined by measurements in chosen surface points both on cold and warm sides of surface temperatures and thermal heat flow density. The surface temperatures were measured using thermocouples and heat flow density – using the heat flow density meter sensors (Fig. 4).

Fig. 4. Location of sensors on specimen for the determination of the thermal resistance

After surface temperatures on cold and warm sides (θ_{si} and θ_{se}) and heat flow density q, W/m^2 are determined, the thermal resistance of specimen could be calculated using the following expression:

$$R_s = \frac{\Delta\theta}{q} = \frac{\theta_{si} - \theta_{se}}{q}. \quad (3)$$

To determine the thermal transmittance through the specimen, first of all, the total thermal resistance R_t, is calculated by adding surface thermal resistances (for internal surface $R_{si} = 0.13$; for external surface $R_{se} = 0.04$ to the previously calculated thermal resistance. Then the total thermal resistance R_t and thermal transmittance U are equal:

$$U = \frac{1}{R_t} = \frac{1}{R_s + R_{si} + R_{se}} = \frac{1}{R_s + 0.17}. \quad (4)$$

The moisture content of fibrous material was determined gravimetrically by weighting before and after drying. The whole mineral wool boards were weighted before they were installed and then again when the wall sections were taken down.

To determine the moisture distribution smaller specimens (square – 100 mm edges) were cut out, prepared and weighted. Specimens were taken both from the edge of the mineral wool board. They were taken sliced into two pieces with a thickness 10 mm and oven dried at a temperature of 105 °C.

RESULTS AND DISCUSSION

The measured temperature values for mineral wool materials are shown as a function of time in Figs. 5 and 6. The values of temperature are shown in Figure 5 for time t ranging from 0 to 5 days. The thermal test data from each of the five layers were used to obtain the thermal resistance of structure. The R_t-values of structure are presented in Fig. 7.

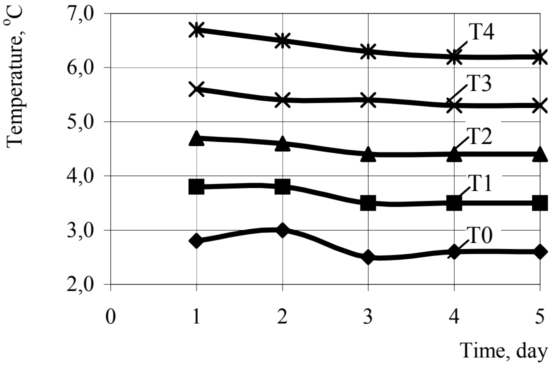

Fig. 5. Measured isotherms of the structure in the cases: indoor and outdoor temperature is +20 and 0 °C, respectively

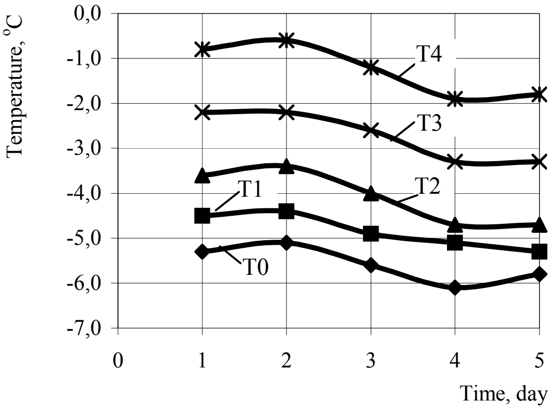

Fig. 6. Measured isotherms of the structure in the cases: indoor and outdoor temperature is +20 and –10 °C, respectively

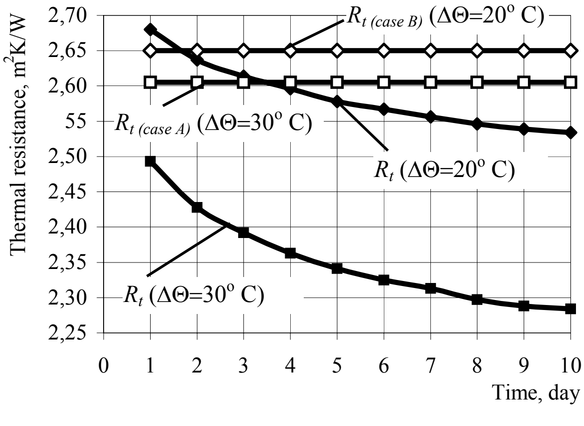

Fig. 7. The dependence of the R-value of the structure

The results presented in Fig. 5 illustrate that temperature of layers have small changes in time while outdoor temperature was about 0 °C. However, the situation is different in the next stage, while outdoor temperature was about –10 °C. The dynamic curves demonstrate the decrease of temperature while structure was exposed in mentioned ambient. According to the results the temperature of layers decreased about 1.0 °C after 5 days. Basing on these results it was stated that accumulation of the moisture in structure has started.

According to the experimental investigation (Fig. 7) the *R*-value of structure (section A) decreased from 2.67 $m^2 \cdot K/W$ to 2.52 $m^2 \cdot K/W$ while outdoor temperature was 0 °C. In this case heat transfer increased approximately 5 – 6 %. During the second stage of experimentation, when outdoor temperature was –10 °C, the *R*-value decreased from 2.45 $m^2 \cdot K/W$ to 2.26 $m^2 \cdot K/W$, so heat transfer increased 15 %.

Analogically to the mentioned above wall, the experimental thermal analysis of structure (section B) was carried out at the same time. The comparison of the results achieved during the experiments shows that, under different outdoor temperatures, the achieved results differ insignificantly. It was determined that R-value of structure was 2.65 $m^2 \cdot K/W$ to 2.61 $m^2 \cdot K/W$ while, outdoor temperature was 0 °C and –10 °C, respectively. This difference may be explained by the heat transfer mechanism: the cold surface of fibrous material was permeable; in this case convection takes place in fibrous insulation material, which increased heat transfer.

After thermal investigation the specimen was dismounted and moisture distribution was investigated. Section A showed undrained water and ice on the external layer below the fibrous insulation (Fig. 8).

a b

Fig. 8. Structure hoarfrost in mineral wool (a) and damp sheet (b)

The results of measurements of moisture contents after 15 days of exposure are presented in Table 2.

Table 2. Mean values of moisture content in mineral wool layers after 15 days exposure

Layer	Moisture content*, vol. %	
	Section A	Section B (Ref. meas.)
0 – 10	11.3	0.15
10 – 20	0.59	0.14

* Average from 5 specimens.

Analyzing the obtained results it seems that it would be reasonable to increase the vapour permeability of the external layer of wall, with the aim to avoid moisture accumulations. However, it was proved by the experiments [11] that external layer must be weatherproof and protect all structure from rain, wind, etc.

CONCLUSIONS AND RECOMMENDATIONS

The results of this study show that the thermal resistance of fibrous thermal insulating material decreases as the materials are installed between two external and internal layer. The *R*-value for structure decreased up to 6 % and to 15 % while outdoor temperature was 0 °C and -10 °C, respectively. Thus, it is clear that reasonable to install ventilated air layer between insulation and external layer.

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