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Investigation of the process of heat transfer in the structure of thermal insulation materials based on natural fibres

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Abstract

Thermal insulation materials based on natural fibres are some of the promising materials that are currently emerging on the construction market. These materials are important especially in terms of sustainable development, since they utilise renewable raw material resources or secondary materials and their production does not consume too much energy. However, a problem with these materials is the rather different behaviour during heat and moisture transport compared with conventional insulation, which is made from synthetic (foam polystyrene) or inorganic (mineral wool) materials. The paper presents the results of a practical investigation into the process of heat transfer through the structure of thermal insulation materials based on natural fibres.

Keywords: Thermal insulation; natural fibres; heat transfer; moisture transport

1. Introduction

The energy performance of buildings is one of the main topics in contemporary civil engineering. The implementation of the requirements of the Directive 2010/31/EU of the European Parliament and the Council brings more strict requirements on the thermal insulation of buildings throughout the EU, including the Czech Republic [1]. The stricter requirements on the thermal protection of buildings are one of the main reasons for the increased

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consumption of thermal insulation materials during the construction of new buildings (as well as the renovation of existing buildings). In order to reduce the environmental strain and material consumption, it is appropriate to insulate buildings with materials made from renewable or secondary materials. The research at Brno University of Technology has for many years been focused on the utilisation of natural fibres (both primary and secondary ones) for the manufacture of thermal insulation materials used in construction. However, there is a problem with the use of these materials, which is their susceptibility to moisture and changes in their thermal insulation properties due to moisture. The behaviour of these materials is different from conventional ones in terms of heat and moisture transfer (e.g. foam polystyrene or mineral wool). This is the reason why many scientific papers address the issue of their hygrothermal behaviour [2,3,4,5].

The heat transfer in the structure of natural fibre-based insulation materials is somewhat different from how it occurs in the structure of conventional ones. The reason is mainly the fact that their structure is formed by fibres of varied length, thickness and orientation. The microstructure of the fibres is also a factor.

As heat and humidity travel through the structure of this insulation, they interact with the fibres and change their water content. This process is very complicated and is unique to each type of fibres. The basic problem is that this changes a number of their properties as well, which then alters the properties of the insulation material as a whole. This involves mainly the following:

- A change in thermal conductivity of the fibres due to moisture – the change in moisture is caused by a shift in the division of the thermal and humidity field in the structure, which alters the sorption properties of the material. There is also moisture that enters the fibre structure as a result of water vapour condensation in the structure. Finally, there is moisture, which is transported through the fibres by capillary suction in the direction of the moisture or temperature gradient.
- A change in the mechanical properties of the fibres due to moisture. Changes in the fibre moisture content alter their mechanical properties, which manifests itself in the change of the fibre stiffness and the change of the insulation's volume stability in a structure. In cases where the insulation is applied loosely in a vertical structure, this may cause the fibres to subside under their own weight.
- A change in the volume of the fibres due to moisture. The volume of the fibres changes together with their mechanical properties. This alters the overall structure of the insulation and the structure becomes denser in cases where the application of the insulation prevents it from increasing its volume. At lower moisture content, this can have a positive effect. Compacting the internal structure of the insulation reduces the degree of heat transfer by radiation and convection, which can outweigh the negative factor of a higher thermal conductivity of the fibres themselves.

Fig. 1. Ice formation on a test sample caused by humid air penetration.

The crucial problem in predicting the behaviour of these materials and creating computational models for the transport of heat and humidity is the complexity of the above-described phenomena and their impact on the behaviour of the insulation. The boundary conditions in relation to time are also very important. For instance, during long-term moisture condensation in the insulation and at a high diffusion flux, moisture is being redistributed towards the outer surface (due to the lower sorption moisture of the material) and, in some cases, it can even freeze (these are extreme cases, which most computational models are unable to account for).

The change in thermal insulation properties in dependence on moisture is best captured in the equation by Meng (1994). Given the nature of the natural fibre-based insulation materials, this equation was identified as optimal during the research performed [6].

$$\lambda_{(w)} = \lambda_{mat\,(w)} \cdot (1-P) + \lambda_{water} \cdot \sum_f w_f \cdot R_f + \lambda_{air} \cdot (P-w) \tag{1}$$

Where: λ_{mat} is the thermal conductivity without pores ($W \cdot m^{-1} \cdot K^{-1}$),
λ_{air} is the thermal conductivity of air ($W \cdot m^{-1} \cdot K^{-1}$),
λ_{water} is the thermal conductivity of water ($W \cdot m^{-1} \cdot K^{-1}$),
P is the volume porosity (-),
w is the moisture (%).

f is the number of the considered pore fraction w_f, R_f is the autocorrelation function expressing the deviation from the real parallel arrangement of pores of the capillaries in the ideal model.

This equation was further adjusted during the research and the moisture factor *R* of the structure was determined (see below). Modified Kiessl's models were used for the actual calculation of the heat and moisture transfer. These models were further adjusted for the purposes of calculating the behaviour of fibrous insulation by research teams at TU Vienna [7].

Nowadays it can be seen that there are many tendencies to take all the important phenomena of heat, air and moisture transport into account simultaneously. Many works and articles on this topic have been published in the last few decades [6,7,8]. Building practitioners are still using simplified calculation tools. These tools are often based on the Glaser models, which are taking into account only vapour diffusion phenomena in a thermal steady state of building composition. Real building components are exposed to environments with highly variable parameters with factors like sun radiation, wind driven rain and so on. Advanced calculation tools based on simultaneous heat, air and moisture equations could predict the real behaviour of the material and give more accurate results. These methods could take into account the dependencies of transport parameters like the thermal conductivity of the diffusion resistance factor on material moisture or temperature. Advanced calculations tools are currently available, however, the problem still remains in the material parameters and nuances of material modelling. Fibrous materials have a high content of air, which is in motion and facilitates the transfer of heat and moisture. Ordinary building materials have mainly a small pore structure with negligible air motion and calculation models for their verification are not correct for fibrous materials.

The chosen materials are tested and the obtained experiment results should be helpful for a better understanding of the differences and provide data for practitioner's decision making and standardization.

2. Methodology and test samples

Based on previous research, the investigation was performed with several series of hemp-based insulation with fibre samples containing no more than 20% of shives. These fibres were made into specimens using the bicomponent bonding method (air-lay) with the addition of 15% of polyester bicomponent fibres. The product bulk density was 35 $kg \cdot m^{-3}$ with average diameter of fibres of 150 μm. The specimen thermal conductivity in steady state was measured in accordance with EN 12667, ISO 8301 depending on moisture content, temperature and bulk density [9,10]. All measurements were performed with temperature difference of 10 K. The dependency between the heat transfer coefficient and moisture was obtained from the measured data and taken into account by the Menger's model.

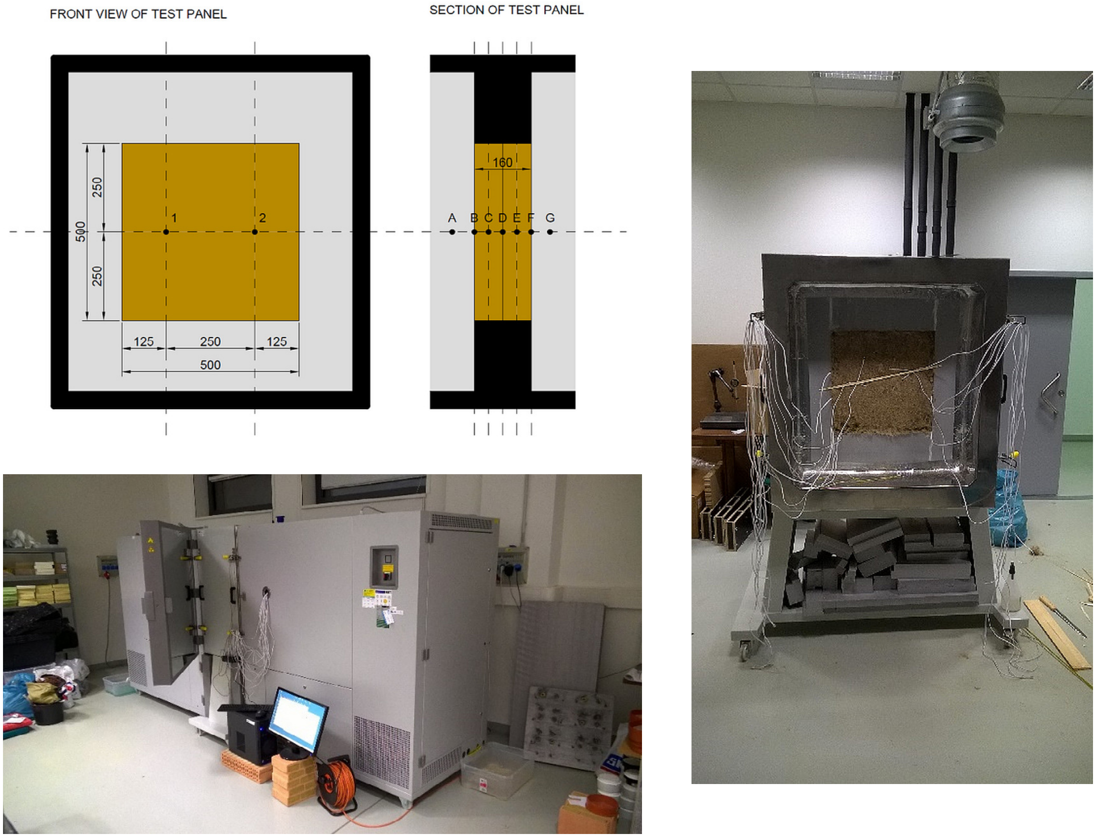

Fig. 2. Diagram of the tunnel with a sample of two hemp insulation layers and the position of 10 sensors and the experimental assembly of test chambers with the tunnel on the left side and a detail of the sample in the test tunnel on the right side.

The data of moisture redistribution behaviour and transport was obtained by exposing the specimen to two environments maintained by climatic chambers with the volume of 600 l. The active area of the specimen was 500 × 500 mm mounted in a mobile tunnel, which was placed between the chambers. Digital sensors for temperature and humidity reading were mounted between the layers of the tested materials. The test assembly and the position of the sensors is showed in Fig. 2. The data from sensors was read every minute during the test. The specimen of the hemp insulation was made from two segments and they were weighed before and after the test for a gravimetric analysis.

3. Results and discussion

Prior to the measurement, the specimens of thermal insulation based on natural fibres were conditioned at a temperature of + 23 °C and relative humidity of 80%. Next, thermal conductivity was determined at a mean temperature of + 10 °C and temperature gradient of 10 K. Before they were measured, the samples were gradually compressed from 0 to approx. 40%, in order to have them assume different bulk densities ranging from 33.7 kg·m^{-3} to 58.8 kg·m^{-3}. It was found that increasing the bulk density reduces thermal conductivity (see Fig. 2). In a state of increased moisture, this behaviour is different from that of dry samples. The reduction of thermal conductivity at low and medium bulk density is more significant in case of moist samples than in dry samples.

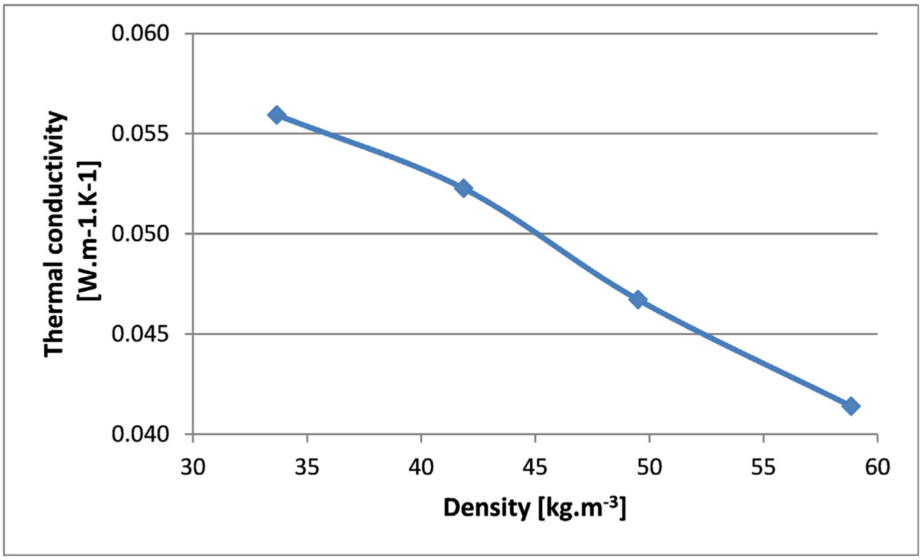

Fig. 3. Dependence of thermal conductivity of hemp based samples with high moisture content on density.

Based on the identified dependencies the computational relation by Meng [6] was modified to the form:

$$\lambda_{(w)} = \lambda_{mat\,(w)} \cdot (1-P) + \lambda_{water} \cdot w\,.\,P\,.\,R_w + \lambda_{air} \cdot (P-w) \tag{2}$$

Where: λ_{mat} is the thermal conductivity without pores ($W \cdot m^{-1} \cdot K^{-1}$),
λ_{air} is the thermal conductivity of air ($W \cdot m^{-1} \cdot K^{-1}$),
λ_{water} is the thermal conductivity of water ($W \cdot m^{-1} \cdot K^{-1}$),
P is the volume porosity (-),
w is the moisture (%),
R_w is the moisture factor structure.

The moisture factor was calculated later and its value was 1.205. Concerning the laboratory model, during the preliminary experiments, there was excessive condensation inside the samples, reaching past 300%. This occurred because the samples were not airtight. For this reason, a vapour proof membrane was placed onto the surface of the samples to stop the air from entering from the chamber into the insulation. The model showed that the moisture inside the insulation equalises and redistributes itself. It equalises throughout the profile of the insulation so that the air in the pore system exhibits a relative humidity of 90–95 % (based on the insulation type and its bulk density). Data from the measurement is showed on the left side of Fig. 4. Drop-out at the begining was substituted by linear interpolation in the charts. The values were obtained from average values in points 1 and 2 for each couple of sensors in layers A-G. The weight of the layers is showed on the right side of Fig. 4. Columns on the left show the weight at beginning of the test and those on the right show the final values at the end.

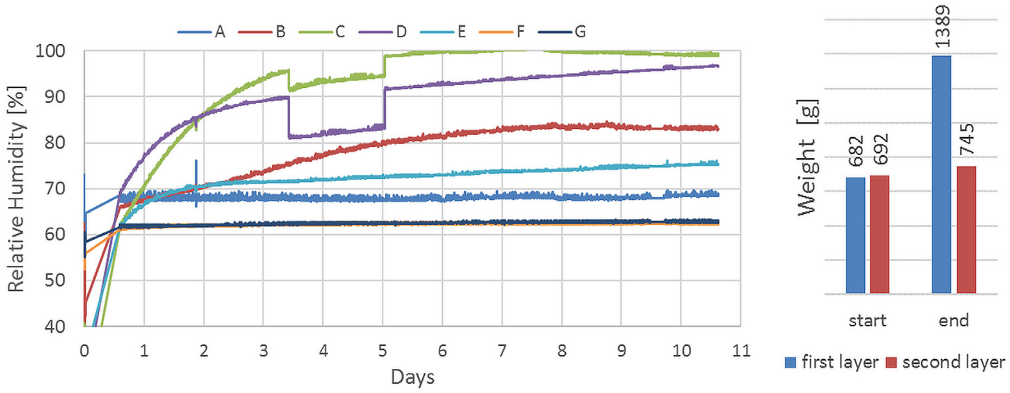

Fig. 4. Average relative humidity course during measurement and the weight of the material layers before and after the test.

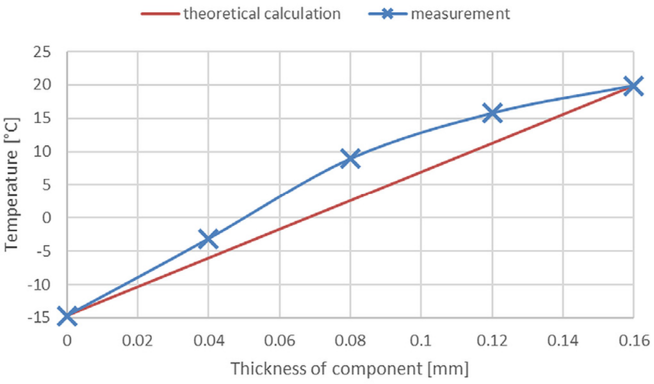

Fig. 5. Temperature distribution in the tested sample at the end of the test.

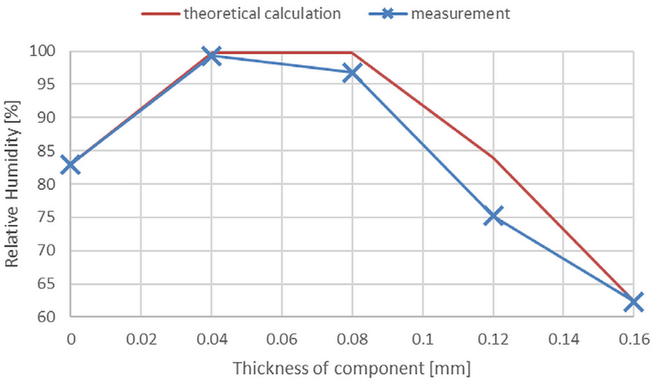

Fig. 6. Distribution of relative air humidity in the tested sample at the end of the test.

As seen from the results in the insulation occurs due to the capillary transport to redistribution of moisture condensate, which has a positive effect on the course of relative humidity in profile of insulator - see Fig. 6. Influence of moisture redistribution is then shown at the graph of temperature course in profile in construction – see Fig. 5, where there is an effect of lower moisture condensate on the thermal insulation properties of the insulator than foreseen theoretical calculation. Some similar results are described in other scientific works [11]. As was found under long time experiments, in case of long time behaviour of natural based thermal insulating materials, moisture transport ins structure is very important, because practical moisture content is one of very important factor affecting final thermal insulating properties of materials heat transition coefficient of all construction.

4. Conclusion

The specimens of insulating materials based on natural fibres were tested for the dependence of thermal conductivity on density and a calculation equation for determining the thermal conductivity for real moisture content was modified. It was found, that (in area of low density) with increase of density thermal conductivity decrease. Dependence of density can be from point of view of practical thermal conductivity value, in case of normal condition of sorption moisture, most important as moisture. The moisture factor R_w [6] was determined on the basis of a back-calculation and reached the value of 1.205.

The experiment shows differences between theoretical assumptions and the measured values. There are other phenomena which must be taken into account. Moisture has a great influence on the temperature distribution and its redistribution occurs as well. If the sample is penetrated by humid air, ice can form in the cold areas. The research is still ongoing, and further findings will be published in the future.

Overall, it was found that the thermal insulating materials based on natural fibers may be in the construction work very well when the good choice of density and with good design of construction composition. Any limited condensation of moisture in the insulation is not necessarily a major problem because it leads to a redistribution of the capillary system of the material.

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