Peculiarities of Determining Thermal Conductivity Coefficient of Low Density Fibrous Materials

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Received 21 September 2001; accepted 14 October 2001

Heat coefficient values of fibrous materials that are discussed in the paper were obtained by measuring constant heat flow and numerical simulating. The following materials were investigated: mineral and glass wool at porosity form 98,6 up to 99,6 %. The main dependencies of heat conductivity on the density, air permeability, layer thickness and mean layer temperature values are presented. Numerical results were compared with the experimental results. The equipment used and the effect of constructional solutions applied on the investigation results were shortly reviewed. Referring to the results of the provided investigation the methods for determination of laboratory value for heat conductivity coefficient λ_{10} of fibrous materials are recommended.

Keywords: thermal insulation, mineral wool, thermal conductivity coefficient.

INTRODUCTION[*]

Building envelopes, under service conditions, are subjected to variable climate changes, which are different on their both exposed sides. On the external face, the conditions are more or less severe due to temperature variation, solar radiation, wind or other weathering conditions. On the internal face, the temperature is usually regulated according to inhabitants' comfort requirements. Therefore, the building components are exposed to two different climates which could have effect on thermal insulating properties. On the other hand, commercially available thermal insulation materials are labeled with a thermal conductivity coefficient value that is achieved at a stated thickness and the same mean temperature that was used in the test [1, 2]. However, the installation of the product can be performed in such a way that the thickness stated on the label is not achieved or surrounding ambient temperature can be different.

Low density flexible insulation in building envelope cavities with heating pipes or with stapling of support flanges inside the cavity could be referred to as common examples in this situation. It means that the λ–value of insulating layer will be different from the declared on the label. Therefore, the study of heat transfer processes in thermal insulating materials leads to the creation of better constructions assuring the required thermal insulating properties for defined service conditions. The knowledge of material properties is necessary to predict the behaviour of buildings linked to their energy consumption.

The heat transfer through low density fibrous assemblies used as insulators is much more complex than that of homogeneous materials [3 - 5]. As we know, the heat is transferred in three different ways: conduction, radiation and convection.

Figure 1 shows an example of dependence of thermal conductivity on the density of insulating material when heat is transferred by conduction and radiation [6].

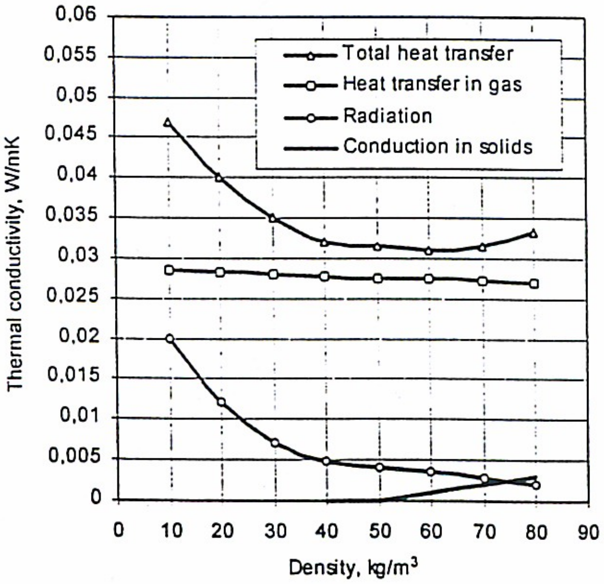

Fig. 1. Heat transfer by conduction and radiation in a fibre glass insulation as a function of insulation density

The apparent thermal conductivity at a specified average temperature, usually 10 °C, is conventionally expressed in terms of density as the following:

$$\lambda = A + B \cdot \rho + \frac{C}{\rho}, \tag{1}$$

The constants A, B and C can be determined by the least square method when values λ and ρ are known. As it is showed in Fig. 1, the values of heat conductivity coefficient for fibrous materials are rising up rapidly at the decrease of density. It could be explained by the increase of radiation part in heat transfer through the air gaps and cavities. On the other hand, the decrease of density for fibrous materials is accompanied with the growth of the air conductivity. Under such circumstances, the heat transfer due to the convection could form in addition to the

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mentioned heat transfer modes. Thus, when the heat conductivity of fibrous materials is examined it is necessary to take into account all the modes of heat transfer as well as the effect of the external factors [7, 8].

This study evaluates the influence of density, air permeability, layer thickness and mean layer temperature values on λ–value of low density fibrous materials. The study contains two parts:

1. Numerical simulation of heat transfer. This part represents a model of the thermal insulating properties of the low density fibrous materials. For simulating purposes the computer program was used.
2. Laboratory tests. Tests were carried out on specimens under different specified conditions.

Determination of thermal conductivity coefficient of low density fibrous materials has been performed at Building Physics Laboratory of the Institute of Architecture and Construction in Lithuania and Building Physics Laboratory of the Technical Research Centre (VTT) in Finland.

METHODS OF INVESTIGATION

Numerical simulation of heat transfer

Simulation was provided by numerical method of solution for a model, which is described in [9]. This program has been developed by CSIRO Division of Textile Physics, Australia, for calculation of one-dimensional heat flow, and it is particularly applied for simulation of heat transfer in fibrous beds. The program calculates the performance by conduction and radiation both through the structure and from fibre to fibre, with sharing or shadowing the radiation by fibres in its path.

A general outline of the parameters of the bed is given in Fig. 2. The bed contains fibres which are randomly oriented and distributed between two parallel infinite boundary surfaces to form an isotropic, homogeneous extinction medium. The fibres are assumed to project a geometric cross-sectional area in all directions. Radiation, which intersects this cross-section, is absorbed in proportion to the fibre surface emissivity, and re-emitted at the temperature of the point emission.

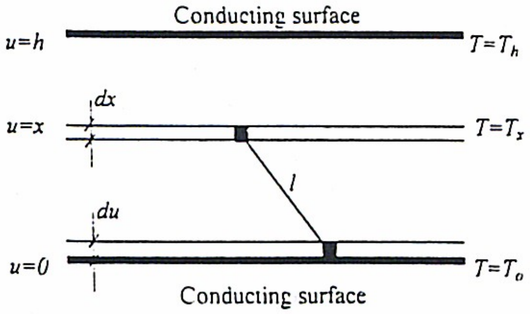

Fig. 2. Elements of the fibre bed

The thermal resistance of the bed is found by dividing the temperature difference by the sum of the two flux components:

$$R = \frac{\Delta T}{q_r + q_c} \cdot \qquad (2)$$

The conducted heat flux q_c through an element of the boundary surface at $u = 0$ is given by the form:

$$q_c = \lambda \left(\frac{\mathrm{d}T}{\mathrm{d}u} \right)_{u=0} ; \qquad (3)$$

where λ is the effective conductivity of the air/fibre composite, and dT/du is the temperature gradient at the boundary surface.

The radiant heat flux q_r through the fibrous bed is given by the following basic expression:

$$q_r = 2 \cdot \sigma \left[e_0 \cdot e_f \frac{1}{k} \int_0^h \mathrm{d}x \cdot x \cdot \left(T_x^4 - T_0^4 \right) \int_x^\infty \mathrm{d}l \cdot e^{-l/k} \cdot l^{-2} + \right. \qquad (4)$$
$$\left. + e_0 \cdot e_h \cdot h^2 \left(T_h^4 - T_0^4 \right) \int_h^\infty \mathrm{d}l \cdot e^{-l/k} \cdot l^{-3} \right];$$

where, σ is the Stephan-Bolcmann constant, e_f, e_o and e_h are the emissivities of the fibres and the conducting boundary surfaces (at ambient temperature), T_0 and T_h are the absolute temperatures of the boundary surfaces at $u=0$ and $u = h$ respectively, $u = x$ is an isothermal plane in the bed perpendicular to the direction of the heat flow and T_x its temperature, l is the distance between the surface element and a volume element anywhere within the bed, and h is the thickness of the bed. The extinction length of the radiation by k, which is the ratio of the fibre diameter to the volume fraction of fibre present.

Assuming the convection to be negligible, the total heat flux through the surface element is equal to the sum of the conducted and radiated components, and once it is established, other thermal properties of the bed could be determined.

The laboratory test

Materials. Measurements of thermal conductivity were made on two commercially available low density fibrous materials groups: glass wool (ρ = 11 - 140 kg/m^3) and rock wool (ρ = 22 - 250 kg/m^3). The fibre diameter of rock wool was as an average 5 µm and the fibre length 4 - 6 mm, and 7 µm and 10 - 15 mm respectively for glass wool.

Apparatus. In the current study thermal resistance measurements were made using an apparatus fitted with heat flow meters on the upper and lower plates (Fig. 3). It conforms to standard ISO 8301 [10, 11]. The dimensions of the cooled and heated plates were 500×500mm, and the dimensions of the measuring plate were 250×250mm.

The test sample is arranged horizontally, so that the heat flow is vertical, either upwards or downwards. The temperatures of the upper plate, lower plate and the surrounding air can be adjusted. In the majority of cases, the temperature of the sample and of the surrounding air was set unchanged at 10 °C [12].

Measurements. Measuring the λ-value of a thermal insulation by the heat flow meter apparatus essentially involves the measurement of the thermal resistance of the material. This can be found by dividing the heat flow density (W/m^2) by the temperature difference (K) across the sample. Fourier's law is used to describe the heat flow through an opaque, homogeneous and isotropic material. This means that there is a linear relationship between the thermal resistance, R and the thickness, d. This means that $R = 1/(\lambda \cdot d)$, where $1/\lambda$ is a constant, representing the slope of the line. If thermal insulation materials with varying thickness are tested under the same test conditions, the results will be in a straight line in R-d coordinate system. In this case, we have a characteristic of the material.

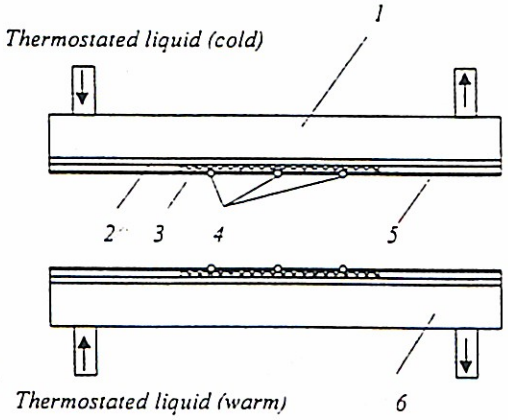

Fig. 3. Scheme of the measuring apparatus: 1 – aluminium cooling plate assembly; 2 –additional thermal insulation; 3 – heat flow meter; 4 – thermocouples (copper-constantan); 5 – black surface; 6 - aluminium warming plate assembly

However, in the paper [13] it is recognised that the heat flow meter apparatus measures the temperature difference, ΔT, and the heat flow density, q, from which the thermal resistance, R, can be calculated. These parameters can be measured even if the heat is transported not only by conduction, e.g. in case of evacuated gap, where the heat is transported solely by radiation, or in low density fibrous materials involving heat transport by conduction, radiation and convection. Dividing the thickness, d, by the thermal resistance, R, gives a property that was sometimes determined as the "measured" or 'equivalent" thermal conductivity. In this case, the λ-value is not a true characteristic of the material but only the result from the certain measurement situation. If some parameters of the test or sample in the test apparatus are altered, the characteristic line should be not a straight line in an R-d coordinate system.

Three test series have so far been carried out in order to study the effect of parameters mentioned above on thermal conductivity. Some of the most interesting results of these measurements have been summarised and presented below.

RESULTS AND DISCUSSION

The effect of sample material density

To evaluate the effect variation of density on the λ-value of thermal insulation the measurements were carried out on rock and glass wool materials at 100 mm thickness and different densities. The results are presented in Fig. 4 and 5.

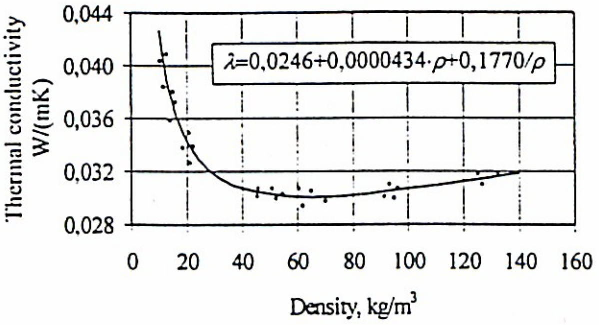

Fig 4. Thermal conductivity of glass wool as a function of its density

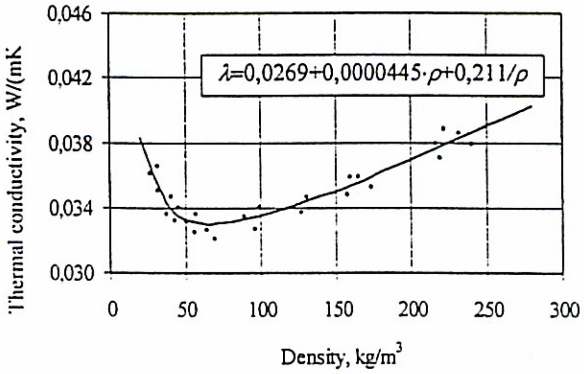

Fig 5. Thermal conductivity of rock wool as a function of its density

It can be seen in Fig. 4 and 5 that thermal conductivity rapidly decreases when the density increases from 10 to 40 kg/m^3 for glass wool and from 20 to 45 kg/m^3 for rock wool. In this case, the radiation is decreased in the cavities of the material, i.e. lowering the density of the fibrous material, the radiative heat transfer increases. It is reasonable to assume that in fibrous materials the heat transfer increases with the increasing mean temperature in the material.

The effect of temperature difference

In order to study the effect of temperature difference on thermal conductivity, a measurement series was carried out on 150 mm thick slabs of glass ($\rho = 10$ kg/m^2) and rock ($\rho = 22$ kg/m^2) wool. All the measurements are provided in a horizontal configuration with the heat flux vertically upwards.

The numerical simulation was performed too. The results are set in Fig. 6 and 7.

The results presented in Fig. 6 and 7 indicate the difference between the calculated and measured values for the higher temperature differences across the sample. It can be explained that numerical simulation program evaluated heat transfer only by conduction and radiation. It is reasonable to assume that such difference could mean an existence of natural convection inside fibrous materials.

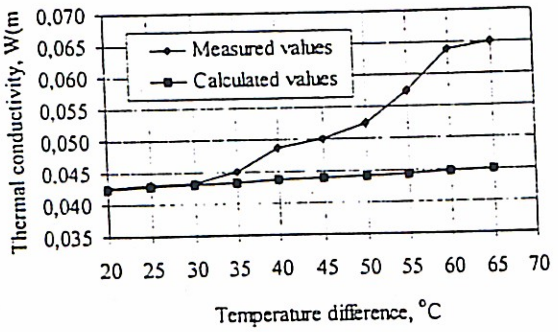

Fig. 6. The effect of temperature difference on thermal conductivity in glass wool

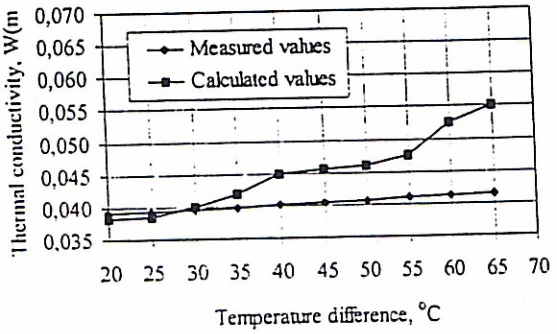

Fig. 7. The effect of temperature difference on thermal conductivity in rock wool

The effect of sample material air permeability

Fig. 8 and 9 show the results of the measurements. As it can be seen the measuring was performed on different air permeability of glass and rock wool specimens.

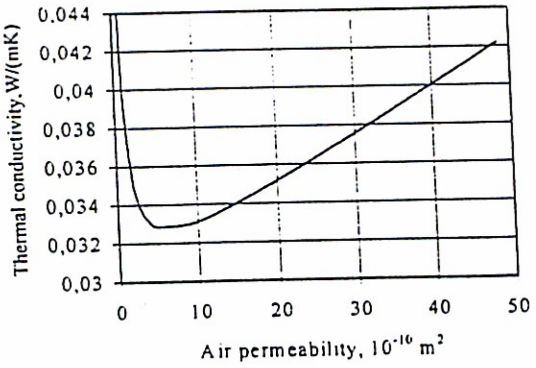

Fig. 8. The effect of air permeability on thermal conductivity in glass wool

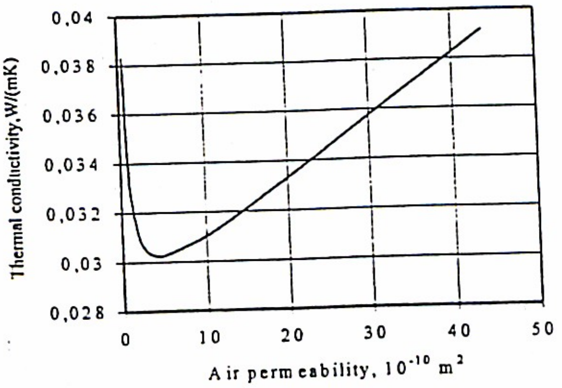

Fig. 9. The effect of air permeability on thermal conductivity in rock wool

The effect of sample material thickness

The analysis of sample material thickness was done using numerical simulation program and laboratory test. The calculations were performed for glass wool with different fibre thickness and different specimen thickness.

The calculations refer to the fibrous material with $\rho = 10$ kg/m^3, fibre conductivity $\lambda = 2{,}5$ W/(mK), fibre surface emissivity 0,8. The temperatures of warm and cold surfaces were 0 and +20 °C, respectively. The results of this test are shown in Fig.10.

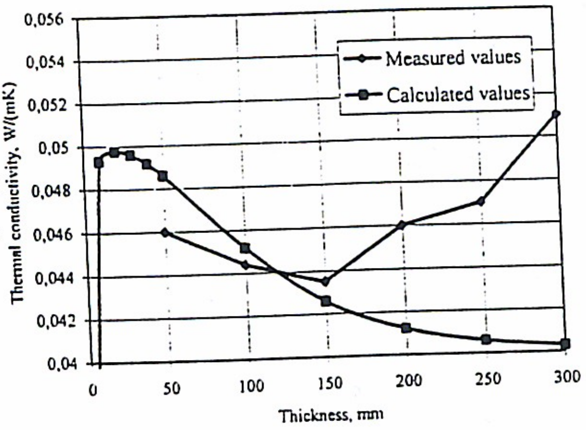

Fig. 10. The effect of sample bed thickness and fibre diameter on thermal conductivity. Comparison of the calculation model with measurements made in the heat flow meter apparatus (500×500 mm)

In order to study experimentally the effect of thickness on thermal conductivity, a measurement series was carried out on the same material samples but different thickness. The results of the measurements were obtained using glass wool specimen ($\rho = 10$ kg/m^3). The measurement series