# Thermal conductivity of mineral wool materials partially saturated by water

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**Abstract**
Thermal conductivity of several types of mineral wool based materials, namely the materials with hydrophobic admixtures, hydrophilic admixtures and without any admixtures is measured in dependence on moisture content from the dry state to the water fully saturated state. An impulse technique is employed for the measurement using both surface and needle probes. The obtained data are analyzed using the Bruggeman effective media concept for different shape of inclusions and the Wiener's basic formulas. It is found that for most materials, the experimental data for thermal conductivity in the range of low moisture content are close to the parallel Wiener's bound but in the range of high moisture content close to water saturation the data are close to the serial Wiener's bound.

**Key words:**
mineral wool, thermal conductivity, moisture content, Bruggeman effective media concept, Wiener's bounds

## 1. Introduction

Thermal properties of mineral wool based materials appear to be of particular importance for their practical applications because the majority of them is used in the form of thermal insulation boards. Every catalogue list of any material producer of mineral wool contains thermal conductivity, sometimes also specific heat capacity but they give only single characteristic values mostly. The dependence of thermal conductivity of common mineral wool on temperature, which is required for instance for pipe insulations, was measured in [1-4]. The dependence of thermal conductivity of mineral wool boards on moisture content was presented in [5]. The effect of natural convection on heat transfer in mineral wool was studied in [6], the radiative behavior of mineral wool was studied in [7,8]. Theoretical considerations on combined heat transfer in mineral wool were published in [9,10].

Many mineral wool products are provided with hydrophobic substances because the presence of water in the material is undesirable for the majority of applications. The main argument for hydrophobization is that the presence of water in mineral wool increases its thermal conductivity several times, which leads to the loss of thermal insulation properties. Hydrophilic additives are seldom used in mineral wool products. However, this kind of materials has a good potential for application for instance in interior thermal insulation systems.

The different treatment of mineral wool fibers in both above mentioned cases leads to different conditions for water appearance in the material. The hydrophobization leads to repulsion of liquid water from the fibers, which is supposed to result in the appearance of water drops in the porous system. On the other hand, hydrophilic admixtures bond water molecules on the fiber surface so that liquid water presence in the porous space is limited. Therefore, the dependence of thermal properties on moisture content will probably be different for materials with hydrophobic and hydrophilic admixtures and the experience cannot be interchanged between these two types of materials.

In this paper, the dependence of thermal conductivity on moisture content is studied for several types of mineral wool based materials, namely the materials with hydrophobic admixtures, hydrophilic admixtures and without any admixtures. The primary aim of this study is better understanding of the effect of water location in the porous system on thermal properties of the studied materials. Therefore, the experimental data are analyzed using a homogenization technique.

## 2. Experimental methods

The thermal conductivity as the main parameter of heat transport was determined using the commercial device ISOMET 104 (Applied Precision, Ltd.). ISOMET 104 is a multifunctional instrument for measuring thermal conductivity, thermal diffusivity, and volumetric heat capacity. It is equipped with various types of optional probes, needle probes are for porous, fibrous or soft materials, and surface probes are suitable for hard materials. The measurement is based on the analysis of the temperature response of the analyzed material to heat flow impulses. The heat flow is induced by electrical heating using a resistor heater having a direct thermal contact with the surface of the sample. The measurements in this paper were done in dependence on moisture content, both needle and surface probes were applied for the sake of comparison.

## 3. Homogenization techniques

Determination of moisture dependent thermal conductivity was done using homogenization techniques as well. In terms of homogenization, a porous material can be considered as a mixture of three phases, namely solid, liquid and gaseous phase. For the materials on the basis of mineral wool studied in this work, the solid phase is represented by basalt fibers, the liquid phase by water and the gaseous phase by air. In case of the dry material, only the solid and gaseous phases are considered. The volumetric fraction of air in porous body is given by the measured total open porosity. In case of penetration of water, part of the porous space is filled by water. For the evaluation of thermal conductivity of the whole material, the thermal conductivities of the particular constituents forming the porous body have to be known. The values of thermal conductivity of basalt, water and air used in this paper were taken from CRC Handbook of Chemistry and Physics [11].

In this work, three Bruggeman-type homogenization formulas (see [12]) were employed. The first of them, the original one, was proposed for spherical inclusions, the second assumes acicular orientation of inclusions and the third was derived for their board orientation. The applied mixing formulas are described in equations (1)-(3), respectively,

$$\lambda_{eff} = \lambda_M + \sum f_j (\lambda_j - \lambda_M) \cdot \frac{3\lambda_{eff}}{2\lambda_{eff} + \lambda_j}, \tag{1}$$

$$\lambda_{eff} = \lambda_M + \sum f_j (\lambda_j - \lambda_M) \cdot \frac{5\lambda_{eff} + \lambda_j}{3\lambda_{eff} + 3\lambda_j}, \tag{2}$$

$$\lambda_{eff} = \lambda_M + \sum f_j (\lambda_j - \lambda_M) \cdot \frac{2\lambda_j + \lambda_{eff}}{3\lambda_j}, \tag{3}$$

where $\lambda_{eff}$ is the thermal conductivity of the studied material, $\lambda_M$ is the thermal conductivity of solid phase (basalt, 3.0 W/mK)), $f_j$ is the volumetric fraction of air or water, $\lambda_j$ is the thermal conductivity of air (0.026 W/mK) or water (0.6 W/mK).

At first, the mixing formulas were applied for the evaluation of thermal conductivity of dry materials. After that, the thermal conductivity of particular materials was assessed as function of moisture content.

For the verification of obtained results, Wiener's bounds [13] for parallel (4) and serial model (5) were used. These bounds in fact represent upper and lower limits of the thermal conductivity vs. water content function. The Wiener's bounds are given in the following relations

$$\lambda_{eff} = \frac{1}{\frac{f_1}{\lambda_1} + \frac{f_2}{\lambda_2} + \frac{f_3}{\lambda_3}}, \tag{4}$$

$$\lambda_{eff} = f_1\lambda_1 + f_2\lambda_2 + f_3\lambda_3, \tag{5}$$

where $\lambda_{eff}$ is the thermal conductivity of the studied material, $f_1$-$f_3$ the volumetric fractions of the particular constituents of the porous body, $\lambda_1$ –$\lambda_3$ the thermal conductivities of the constituents.

## 4. Materials and samples

Mineral wool materials analyzed in this paper were produced specifically for testing purposes by Rockwool CZ, SA. Basic characteristics of mineral wool materials concerning the type of admixture and bulk density are given in Table 1.

Table 1 Basic characteristics of mineral wool materials

| Material | Type of admixture | Total open Porosity [%] | Bulk density [kg/m$^3$] |
|---|---|---|---|
| CNL | Hydrophobic | 88 | 270 |
| CNR | Hydrophobic | 87 | 110 |
| TCR | No admixture | 91 | 90 |
| STR | No admixture | 94 | 120 |
| INH | Hydrophilic | 93 | 210 |
| INS | Hydrophilic | 96 | 90 |

The specimens were cut from the material boards delivered by the producer. The size of the specimens for the determination of thermal conductivity was 50 x 50 x 20-50 mm. Always five specimens of particular material were used for every measurement.

## 5. Results and discussion

The results of thermal conductivity measurements using both needle and surface probes are summarized in Figs. 1, 2. The thermal conductivity of dry materials and materials with the moisture content within the hygroscopic range was dependent practically on the bulk density only. The materials with the bulk density approximately 100 kgm$^{-3}$ achieved the λ values of about 0.04 W/mK, those with bulk density above 200 kgm$^{-3}$ had λ a little higher, around 0.05 W/mK. This is in a good agreement with the reference data (see e.g. [1]). In the hygroscopic moisture range the data obtained by both needle probe and surface probe differed only within the error range of the measuring method.

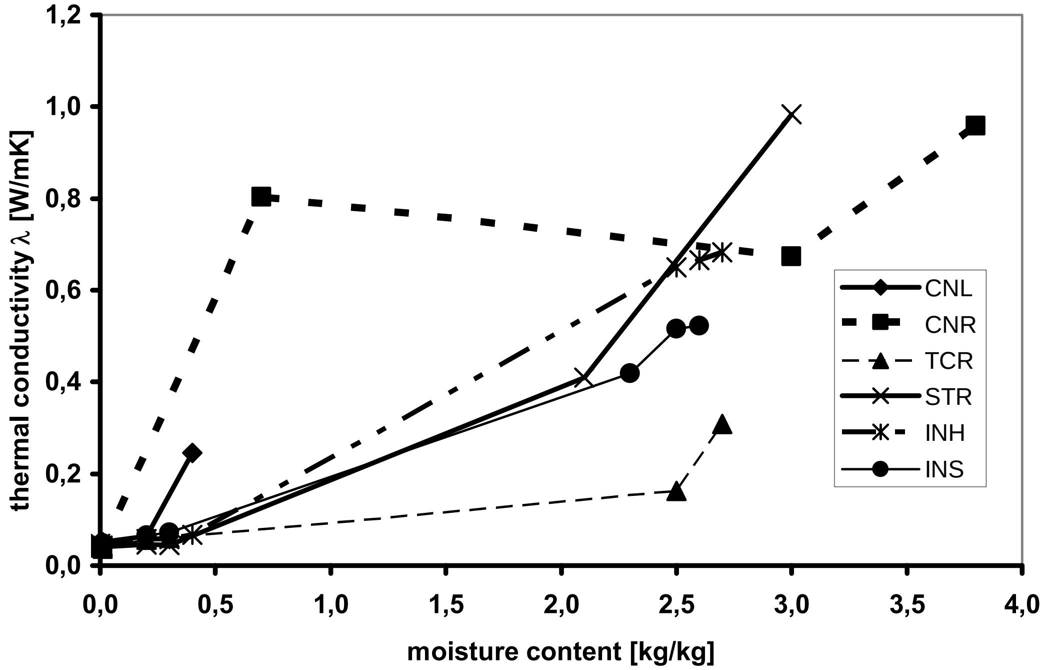


Fig. 1 Experimentally determined thermal conductivity of mineral wool materials in dependence on moisture content in the direction along the fibers, i.e. using the needle probe

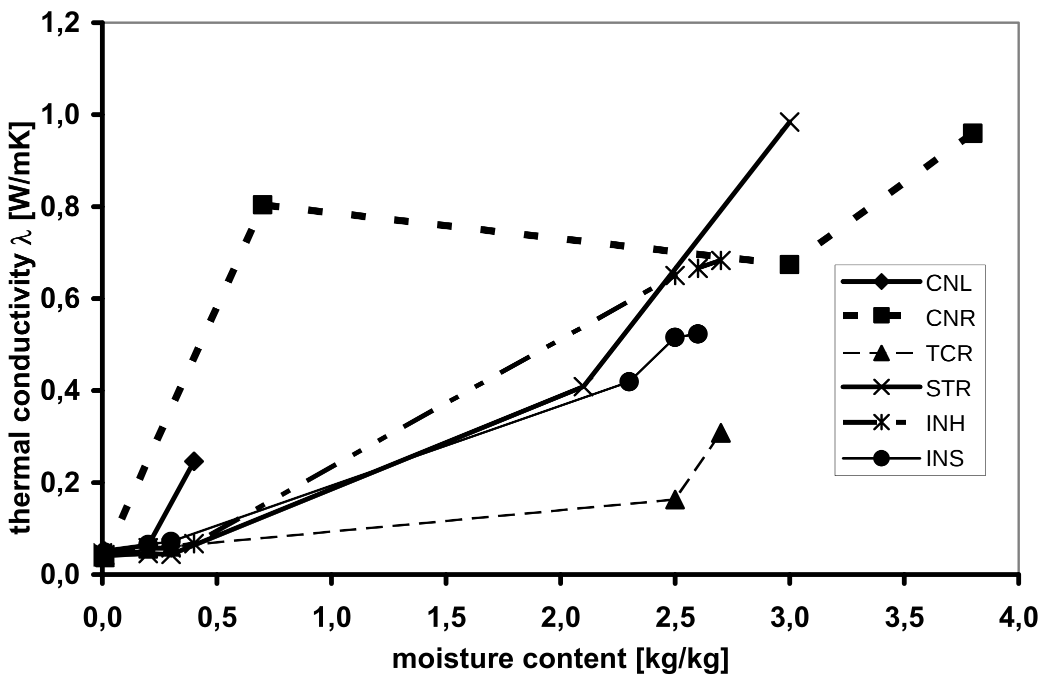


Fig. 2 Experimentally determined thermal conductivity of mineral wool materials in dependence on moisture content in the direction perpendicular to the fibers, i.e. using the surface probe

The thermal conductivity data obtained for specimens with moisture content in the overhygroscopic range exhibited much higher differences between the particular materials and particular probes.

For the hydrophilic materials INH and INS the differences between data obtained by needle and surface probe were systematic. The surface probe always gave higher $\lambda$ values. In an explanation of this fact it is necessary to take into account that the surface probe measures in fact the thermal conductivity in the direction perpendicular to the fibers while the needle probe in the direction along the fibers. In the hydrophilic mineral wool materials water is localized on the surface of the fibers. Therefore, a surface probe can achieve a contact with the material on whole its surface. On the other hand, a needle probe crosses the fibers and some parts of the probe are still in contact with the remaining air in the material. So, the character of differences in data obtained by both type of probes seems to be logical. It should be noted in this respect that for a thermal insulation material, the thermal properties in the direction across the board that are commonly applied for determination of thermal resistance of the board are of higher importance than its properties along the board that could only be utilized in 2-D calculations. Therefore, in standard building-physics related calculations the data obtained using surface probe are to be used.

Looking at the results from the quantitative point of view, for the material INH the surface-probe $\lambda$ values for the highest moisture contents are slightly higher and for INS slightly lower than the thermal conductivity of water (0.60 W/mK for $20^0$C – see [11]). This seems to be a logical result again. The higher bulk density material INH contains a higher amount of fibers per unit volume and it can be assumed that most of voids are full of water. So, the final thermal conductivity should be somewhere between the thermal conductivity of water and basalt (3.0 W/mK - see [11]). The lighter material INS containing a lower amount of fibers per unit volume certainly retained more air voids than INH even in the layer close to the material surface. These voids then lowered the measured $\lambda$ values.

The thermal conductivity data of hydrophobic materials and materials without any admixtures in the overhygroscopic range exhibited differences looking quite random. The results obtained with the surface probe were sometimes higher, sometimes lower than those with the needle probe. In some cases, the $\lambda$ values even decreased with increasing moisture content (for instance CNR). This corresponds with the presumed character of water distribution in this type of materials. The hydrophobization prevents water from the direct contact with fibers, and even the mineral fibers without any surface treatment have a very low wettability. Therefore, water in the material is presented mostly in the form of droplets that can be distributed in quite a random way.

In the quantitative sense the worse contact of water with fibers has led for hydrophobic materials and materials without any admixtures in some cases to an increase of thermal conductivity (CNR and STR) to about 1.0 W/mK. This was possibly due to the effect of higher thermal conductivity of basalt. On the other hand, the thermal conductivity of TCR and CNL was lower, down to about 0.30 W/mK. This was presumably due to the effect of the remaining air in the voids.

The thermal conductivity vs. moisture content functions calculated using three Bruggeman-type mixing formulas and two Wiener’s formulas are presented for each studied material and for both needle and surface probes in Figs. 3 – 14, where $w$ [$m^3/m^3$] is the volumetric moisture content.

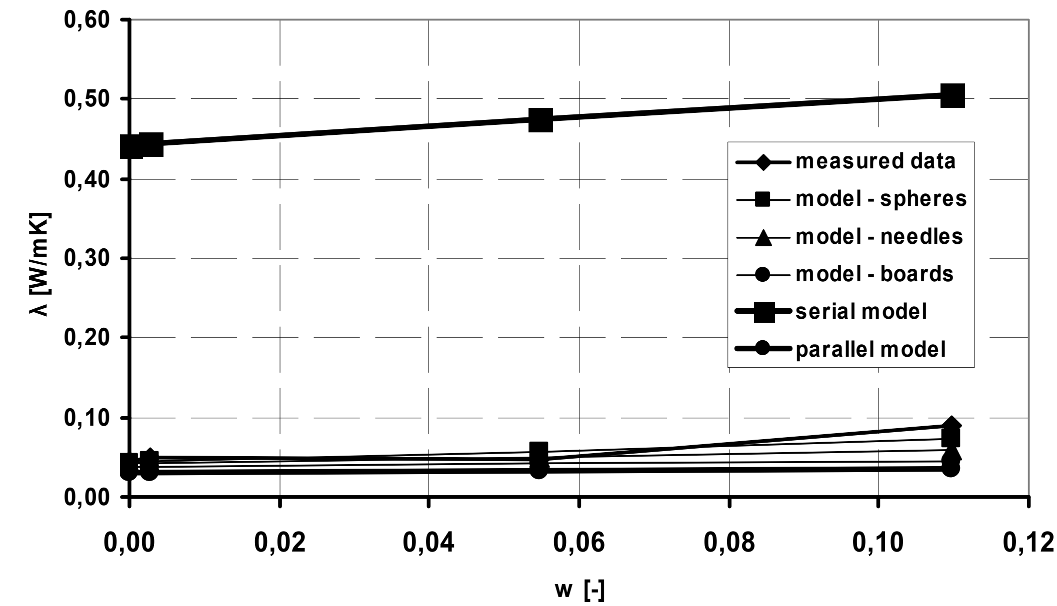


Fig. 3 Thermal conductivity of CNL in dependence on moisture content measured by the needle probe and calculated by mixing formulas

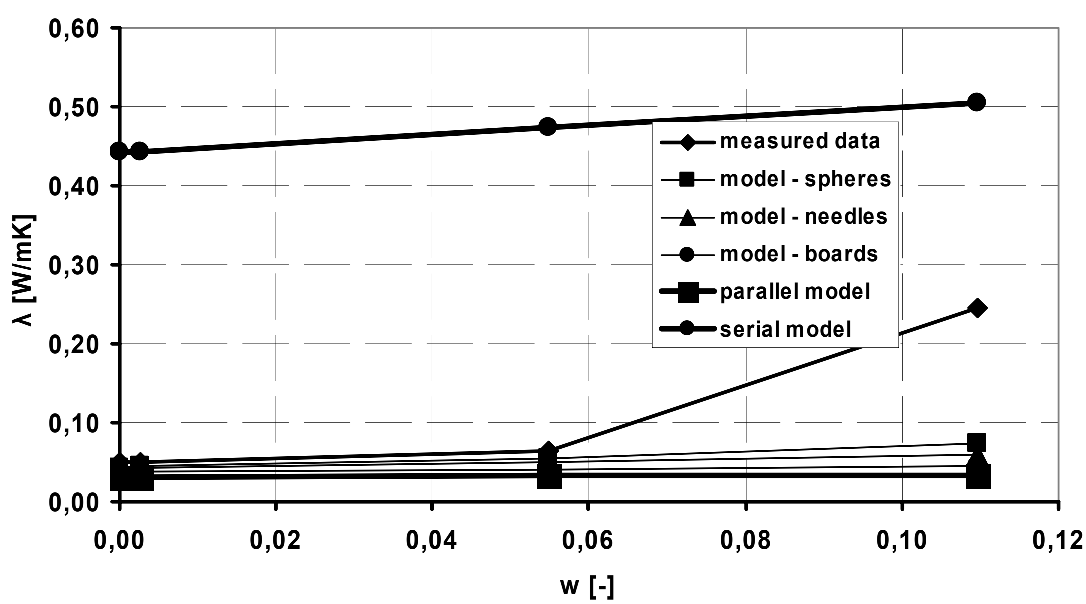


Fig. 4 Thermal conductivity of CNL in dependence on moisture content measured by the surface probe and calculated by mixing formulas

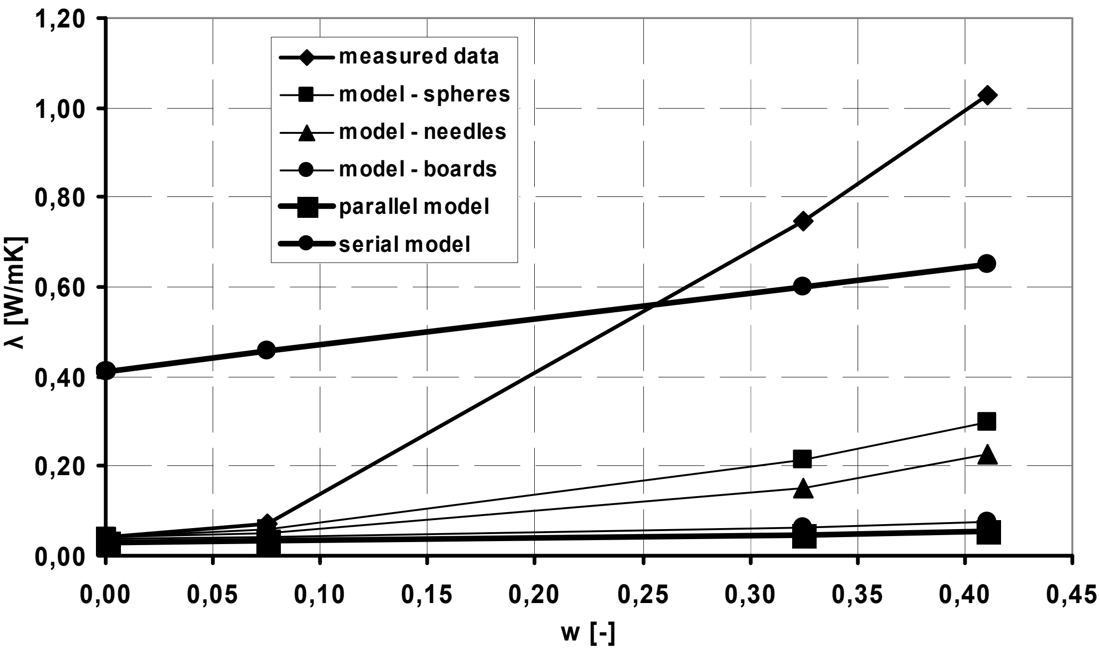


Fig. 5 Thermal conductivity of CNR in dependence on moisture content measured by the needle probe and calculated by mixing formulas

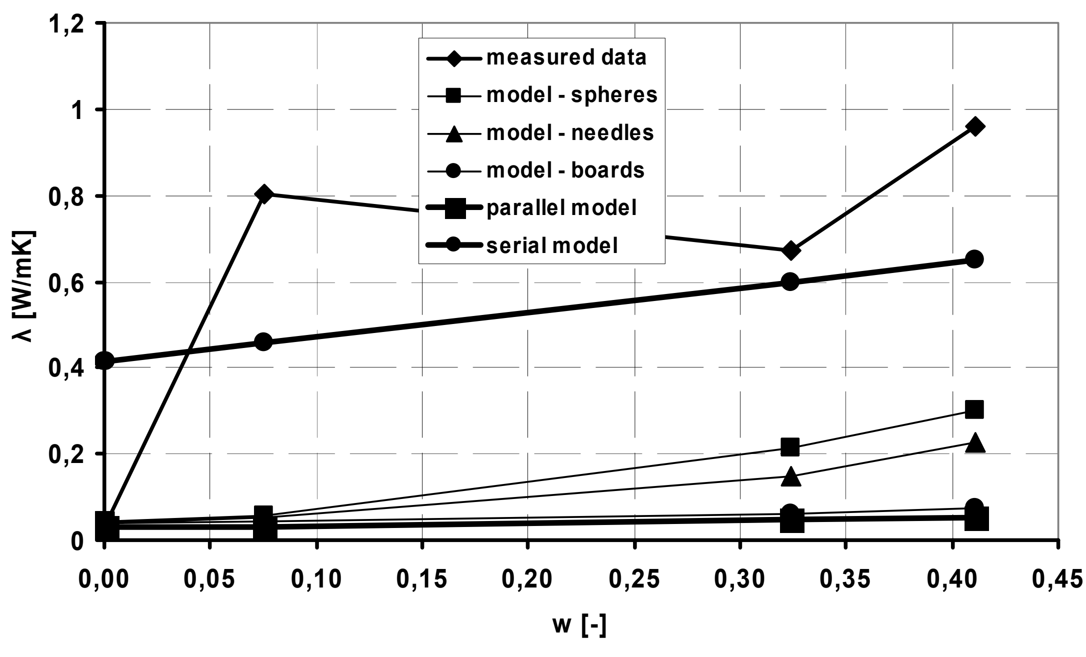


Fig. 6 Thermal conductivity of CNR in dependence on moisture content measured by the surface probe and calculated by mixing formulas

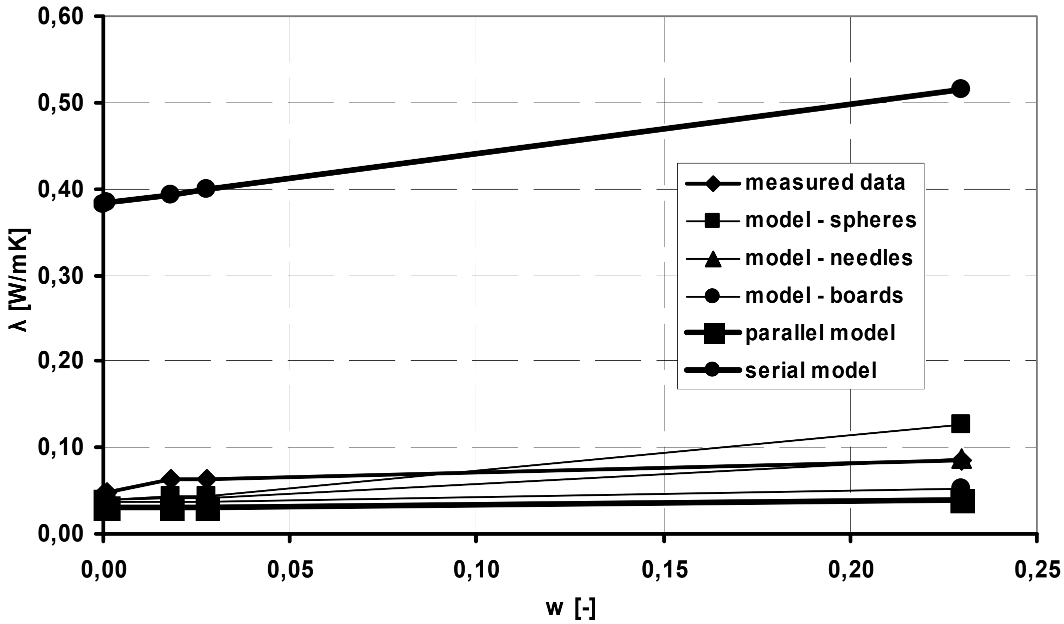


Fig. 7 Thermal conductivity of TCR in dependence on moisture content measured by the needle probe and calculated by mixing formulas

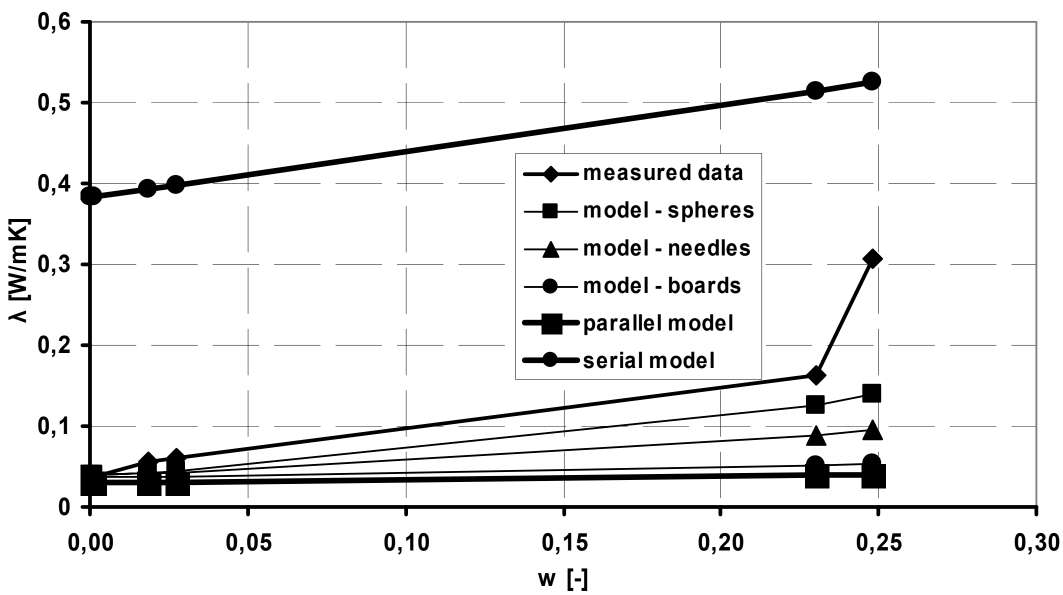


Fig. 8 Thermal conductivity of TCR in dependence on moisture content measured by surface probe and calculated by mixing formulas

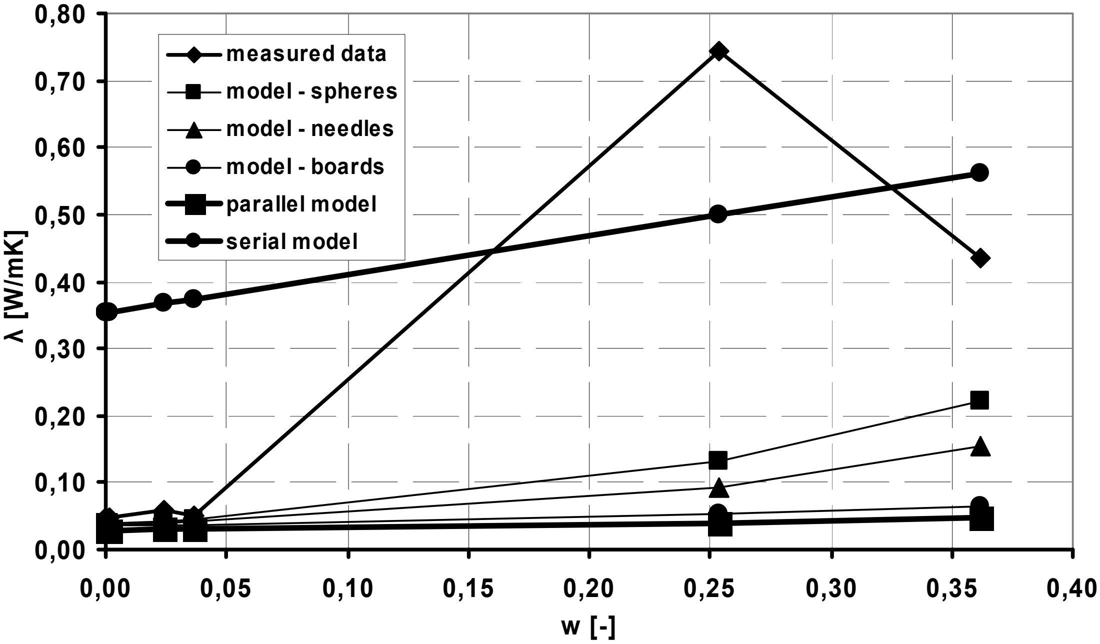


Fig. 9 Thermal conductivity of STR in dependence on moisture content measured by the needle probe and calculated by mixing formulas

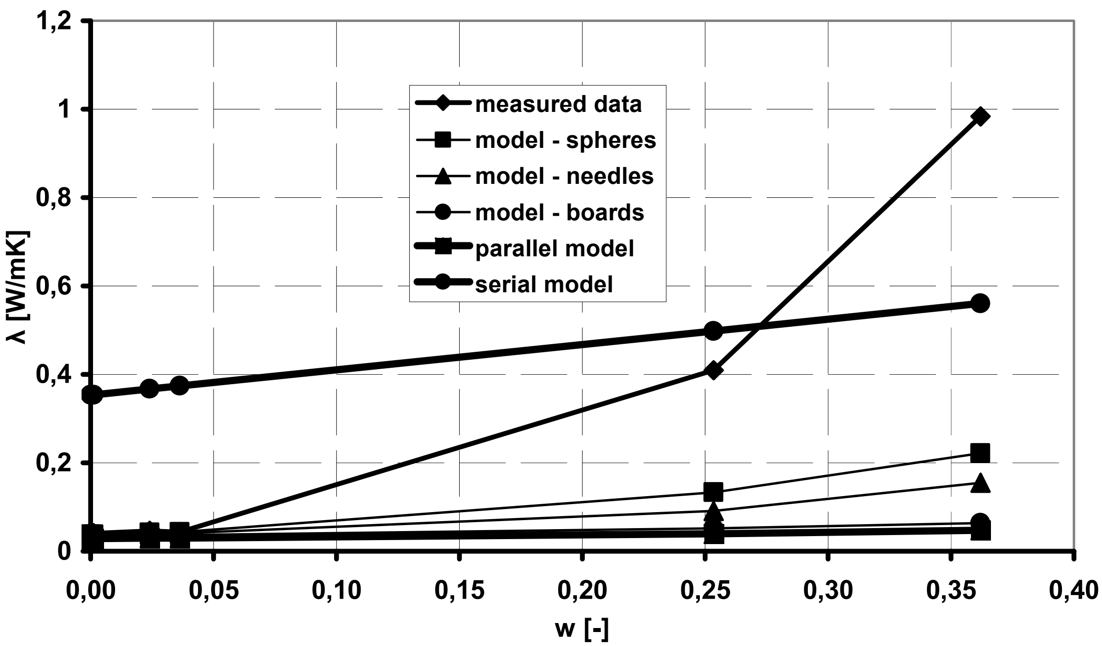


Fig. 10 Thermal conductivity of STR in dependence on moisture content measured by the surface probe and calculated by mixing formulas

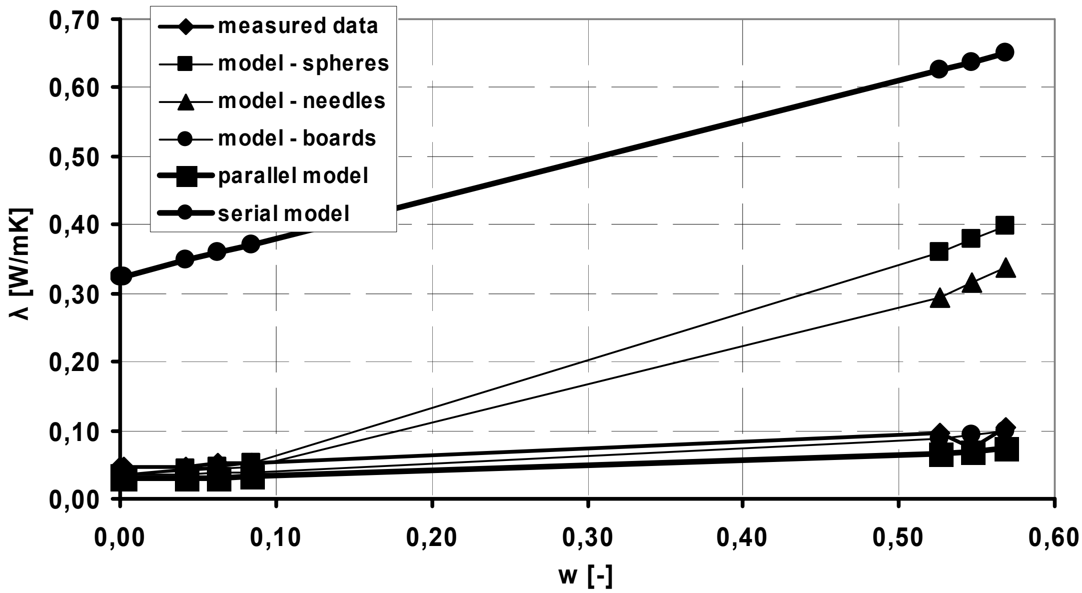


Fig. 11 Thermal conductivity of INH in dependence on moisture content measured by the needle probe and calculated by mixing formulas

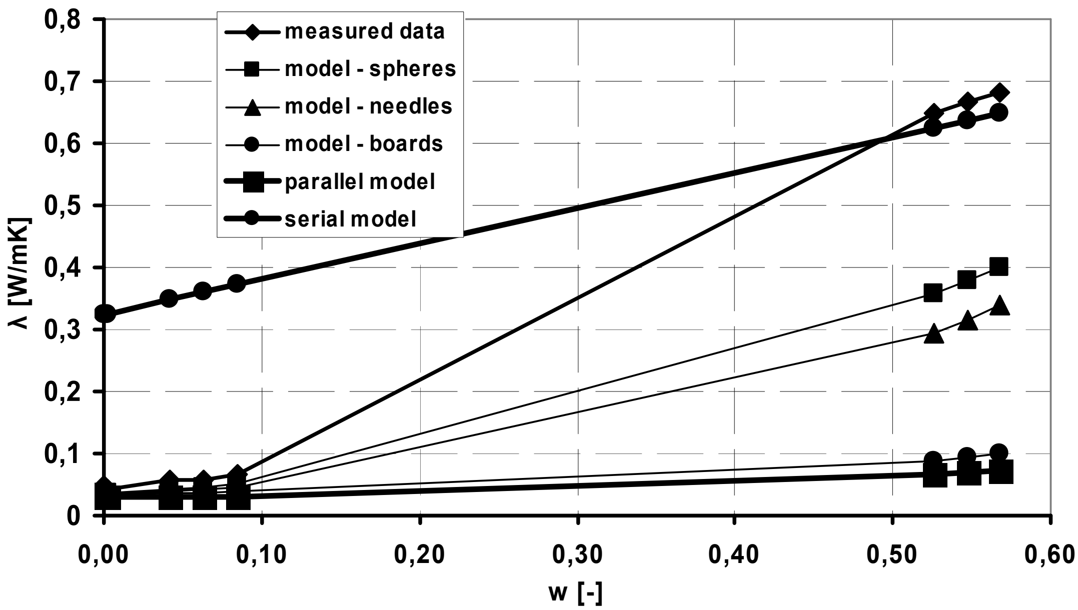


Fig. 12 Thermal conductivity of INH in dependence on moisture content measured by the surface probe and calculated by mixing formulas

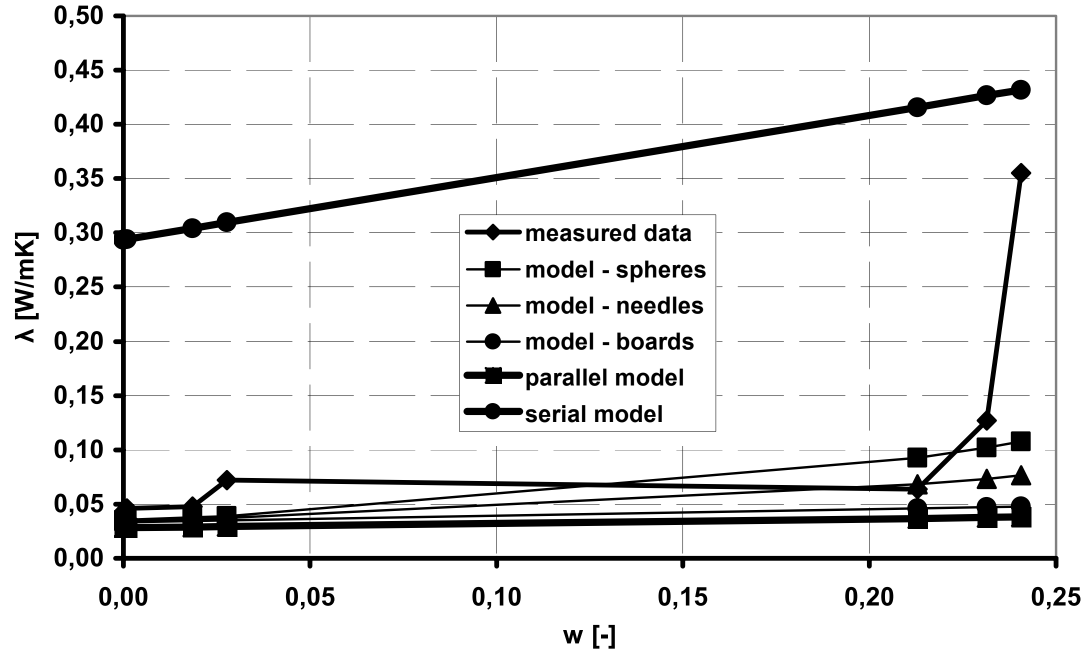


Fig. 13 Thermal conductivity of INS in dependence on moisture content measured by the needle probe and calculated by mixing formulas

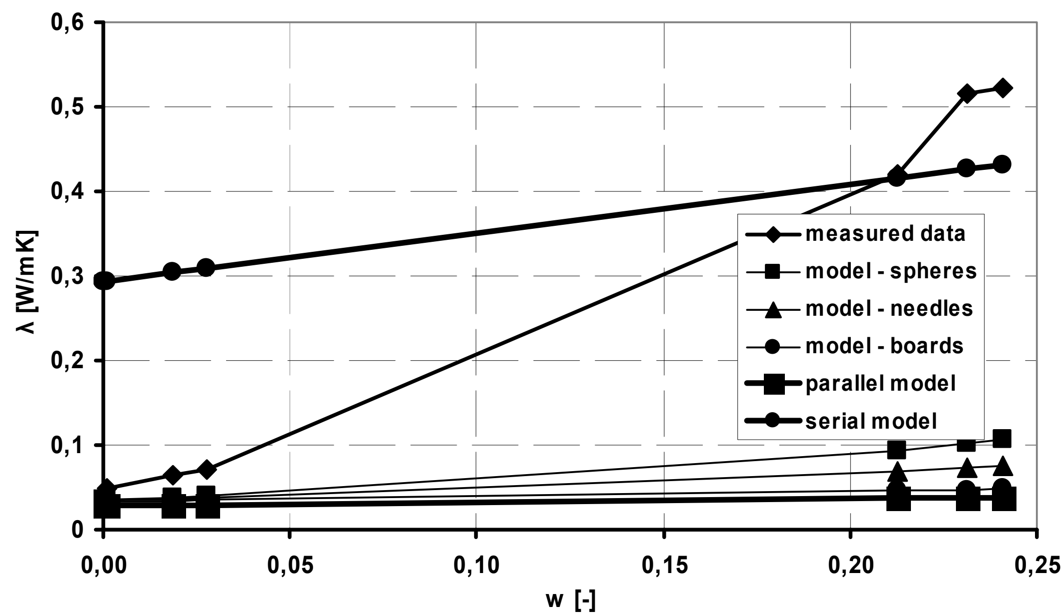


Fig. 14 Thermal conductivity of INS in dependence on moisture content measured by the surface probe and calculated by mixing formulas

Looking at the results from the point of view of Wiener's bounds, we could see that the measured data for the materials CNL, TCR, INH and INS met them well, but the data for CNR and STR were out of these bounds in substantial parts of the $\lambda(w)$ functions. This basically confirms the assumptions on consequences of water location in the particular types of materials given above. However, the bulk density of mineral wool materials appeared to be also an important parameter because CNR and STR had lower bulk density than CNL and TCR which contained the same type of fiber treatment. The most probable reason for this finding was that higher-density materials had a more rigid structure and the presence of water did not lead to substantial deformation while for the lower-density materials with hydrophobic admixtures and without admixtures the dimensions of the specimens changed significantly after penetration of higher amount of water.

The analysis of obtained results from the point of view of the effect of moisture content on the agreement between the experimental and calculated data showed that the experimental and calculated values of thermal conductivity of all investigated materials in dry state corresponded well for both sensors and all three Bruggeman-type formulas. The observed differences between the particular models were very low, especially taking into account the measuring error of the employed device which could be considered as ±10%. The experimental results determined by the needle probe were also very close to the parallel Wiener bound. The same good agreement was also obtained for lower content of water in materials, typically up to $0.05 m^3/m^3$.

On the other hand, the agreement between experimental and calculated thermal conductivities determined for high moisture content differed significantly for different types of materials and different probes. For the hydrophilic materials INH and INS the data obtained by needle probes were close to the parallel Wiener's bound and the data measured by surface probe were close to the serial Wiener's bound. This was in a qualitative agreement with the presumed effect of water localized on the fiber surface in this type of materials. For the dense hydrophobized material CNL and for the material TCR without any admixture all data were close to the parallel Wiener's bound which was clearly due to the lower volume fractions of water. The lower density hydrophobized material CNR and the material TCR without any admixtures generally followed the trend observed for INH and INS but the thermal conductivities exceeded the serial Wiener's bound as it was analyzed before.

## 5. Conclusions

The results of measurements and calculations of thermal conductivity of six different types of mineral wool materials in a wide range of moisture content in this paper have shown that the application of homogenization techniques can provide useful estimates of measured data even for these highly inhomogeneous materials. However, a unified formula could not be found in the whole range of moisture content studied. For most materials, the experimental data for thermal conductivity in the range of low moisture content were close to the parallel Wiener's bound but in the range of high moisture content close to water saturation the data were close to the serial Wiener's bound. Using the Bruggeman-type formulas which were proved as useful in a variety of previous applications was not a successful solution in our case and there is an open question if utilization of more sophisticated mixing formulas would lead to better results.

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