# Influence of temperature and moisture content on the thermal conductivity of wood-based fibreboards

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## Abstract

Temperature and moisture content are important parameters affecting thermal properties of wood and wood-based materials. Quantitative data are required to better characterize the thermal performance of fibreboards. The aim of this work was to assess thermal conductivity of insulation fibreboards at different temperatures (ranging from -10°C to +60°C at 10°C increments) and moisture contents (gravimetrically determined after conditioning at 15%, 50%, 85% RH). Thermal measurements were done conducted with at stationary boundary conditions. The relationship between thermal conductivity, temperature and MC of samples was found by fitting data to a second order polynomial function. Moisture behavior was characterized by applying the Hailwood-Horrobin (H-H) sorption model. The single-hydrate model was used with the equilibrium moisture data at each conditioned climate step, starting at 10% RH, up to 90% RH, at 10% RH increments. Total sorption as a composite of hydrated and dissolved water sorption was quantified for adsorption as well as desorption. Modelled data were in close agreement with the experimental data. Accurate datasets on the thermal behaviour of insulation materials are crucial in numerical modelling approaches, which will improve the proper design of building envelopes.

**Keywords**

*Thermal conductivity, Heatflow meter (HFM), Adsorption isotherm, Hailwood-Horrobin model*

# 1. Introduction

According to DIN EN 316 standard low-density fibreboards are porous panels having a density between 230 kg/m$^3$ and 400 kg/m$^3$. They are usually wet-laid, with very low additions of adhesives and sizing agents (Maloney, 1993; Youngquist, 1999). Nowadays, different new dry-processes are used to manufacture very low density fibreboards (about 50 kg/m$^3$) with better thermal insulation parameters (Barbu, 2012; Xie 2011). Low-density fibreboards usually refer to insulation boards as they are mainly used as thermal insulation materials in civil engineering. They are often subject of strong temperature and humidity changes especially when installed as facade insulation. The expressed changes of environmental conditions cause alterations of physical properties. One of the negative consequences due to varying moisture contents are unwanted dimensional changes. Because of shrinking and swelling of the material visual and structural problems occur, including splitting, development of decay and stain fungi, and loss of mechanical strength. Along with the moisture changes, the thermal conductivity may also alter (Steinhagen, 1977).

To combat unwanted changes of moisture in wood-based panels, hydrophobic additives might get added (Jiřičková et al., 2006). These additives, however, may also lead to changed thermal characteristics (Sonderegger and Niemz, 2012). The transportation of heat through the panel is driven by the proportion of voids (Smith, 1997; Bekhta and Dobrowolska, 2006). Herein, the positive dependency of thermal conductivity on temperature plays an important role, and becomes decisive in the case of e.g. sun exposed facades (Gur'ev and Khainer, 1999). Thermal conductivity of fibreboards increases with increasing temperature linearly about 0.45% per Kelvin in the range of 10°C to 30°C (Sonderegger and Niemz, 2010). Thermal conductivity depends also on the manufacturing method of the boards, mainly on the orientation of fibres, the porosity distribution and the glue fraction (Sonderegger, 2011).

There is a number of ways to measure thermal conductivity. The steady-state technique measures conductivity when the material is in complete equilibrium (Salmon, 2001). The heatflow meter technique uses two calibrated heatflux transducers with the specimen placed in between. A steady-state heatflux is maintained by applying a given thermal gradient across the specimen. Thermal conductivity is then evaluated according to Fourier´s law (Siau, 1984). Yu et al. (2011) used a guarded heatflux method to establish thermal conductivity of commercially produced wood-based panels. The influence of moisture content and temperature on the thermal conductivity of insulation fibreboards by heatflow measurements was shown by Matias et al. (1997). The investigation of thermal conductivity and moisture behavior of fibreboards including sorption and desorption curves was carried out by Brombacher et al. (2012) at temperatures between 10°C and 30°C. Further work refers to relationships between thermal conductivity of wood-based composites and density, as well as different particle sizes (Sonderegger and Niemz, 2012) and (Sonderegger and Niemz, 2009).

The vapor sorption behavior of wood fibres is comparable to solid wood, as shown before (Scheiding, 1998). The Hailwood-Horrobin (H-H) model or Dent model has been frequently applied to fit the experimental data related to vapor sorption of wood With the H-H model, sorption isotherms of wood and other natural fibres can be assessed (Hill et al., 2009).

The purpose of this work was to assess and quantify the influence of temperature and moisture on the thermal conductivity of insulation fibreboards.

To comply with European standards, insulation board manufacturers usually provide thermal conductivity data measured at 23°C and 0% moisture content. As thermal conductivity is changing with temperature and moisture content, data and relationships addressing these dependencies are required, to better quantify insulation performance. The specific research objectives are therefore as followed: a) characterize the influence of temperature and moisture content on thermal conductivity of fibreboards, and b) evaluate the moisture behavior of the material using the sorption and desorption isotherms using the Hailwood-Horrobin model. The aim of the present study was also to obtain accurate parameters suitable for a wider range of temperatures and moisture contents, to numerically model coupled moisture and heat transfer processes in wooden buildings.

## 2. Material and methods

Commercially available, wet-processed insulation fibreboards with a thickness of 35 mm were provided by the Hofatex® company. Spruce and fir chips were used as a raw material for the fibreboard production. No adhesives were added to the mixture of water and fibres. Hydrophobicity of the boards was improved by the addition of 1.5% paraffin. Aluminium sulphate (7-8%) was added to accelerate curing and hardening. Final fibreboards were glued by using the starch adhesive. The insulation fibreboards are commonly used as thermal roof insulation, outer building sheathing or ceiling facing. The thermal conductivity was 0.049 $W.m^{-1}.K^{-1}$, based on ISO 8301:1991, determined at oven-dry conditions. Ten samples sized 600 mm x 600 mm were cut, and dried in a Sanyo MTH 2400 chamber at 60°C until weight constancy (< 0.1%). Constancy of the density was checked after the heatflow measurements. For this, four small samples (50x50x35 mm) were cut from the middle part of each board. Mean gravimetric density was 243 $kg.m^{-3}$, with the coefficient of variation being as low as 0.58%.

Thermal conductivity was measured across the thickness of the board using the heatflow meter HFM 436 Lambda by Netzsch®. The fibreboard samples were placed between the two heated platens with the heatflux sensors installed (Figure 1). Thermal conductivity was determined as soon thermal heatflow equilibrium has been reached at the defined temperature difference. The heatflow meter was calibrated with the standard fiberglass board NIST 1450b, having a thickness of 25 mm. Heatflow was detected in the midpoint of the sample, representing an area of 300 mm by 300 mm. The full size of 600 mm x 600 mm was needed to ensure steady-state thermal conditions for the measured area. The temperature difference between the hot and a cold plate was set to 10°C. We have used a set of eight temperature points, ranging from -10°C to +60°C, at 10°C increments. All samples were conditioned at 20°C, and 15%, 50%, 85% relative humidity (RH) in a Sanyo MTH 2400 air chamber, respectively. Samples were wrapped in thin and transparent foils (thickness 0.01 mm) to keep moisture losses at a minimum. Samples were weighed before and after the heatflow measurement to ensure stable moisture contents. Moisture losses were recorded, and the foil-effect on thermal conductivity was also assessed.

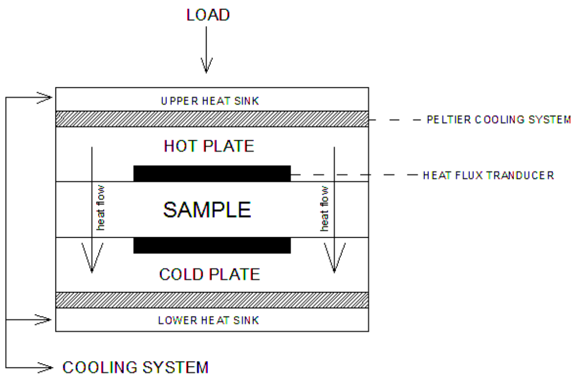



**Fig. 1** Heatflow measurement setup for the tested insulation fibreboards.

Adsorption and desorption isotherms were obtained by testing 50 samples with the approximate dimensions of 50 mm x 50 mm x 35 mm. Equilibrium moisture contents (EMC) were measured (after reaching weight constancy < 0.1%) at 20°C, starting at 10% up to 90% RH, with 10% RH increments (conditioned also in the air chamber). Prior to the sorption tests the samples were dried at 60°C. Desorption measurements started from 90% RH reached by adsorption. Therefore, desorption isotherm represents rather a scanning curve than actual desorption boundary curve.

The Hailwood-Horrobin (H-H) model (Simpson, 1980) as the most used model for the prediction of EMC in wood was applied. Here, the single-hydrate model was used with the equilibrium moisture data at each conditioned climate step. The constants A, B, C (1) and coefficients of the H-H model (2) were obtained through fitting a second order polynomial function to the experimental data, following (Skaar, 1988). Goodness of fit was indicated by the coefficient of determination ($R^2$). The total sorption isotherm (3) was determined from the sum of hydrated (4), and the dissolved (5) water,

$$\mu = \frac{\varphi}{A + B.\varphi - C.\varphi^2} \tag{1}$$

$$K_1 = \frac{-B + \sqrt{B^2 + 4.A.C}}{2.A} \qquad K_2 = 1 + \frac{B}{A.K_1} \tag{2}$$

$$M_{total} = M_{hyd} + M_{dis} \tag{3}$$

$$M_{hyd} = \left(\frac{100}{\sqrt{(B^2 + 4.A.C)}}\right).\left(\frac{K_1.K_2.h}{1 + K_1.K_2.h}\right) \tag{4}$$

$$M_{dis} = \left(\frac{100}{\sqrt{(B^2 + 4.A.C)}}\right).\left(\frac{K_1.h}{1 - K_1.h}\right) \tag{5}$$

with μ being the moisture content [-]; φ the relative humidity [-]; A,B,C the regression fitting constants, $K_1$, $K_2$ the coefficients calculated for the Hailwood-Horrobin model, $M_{hyd}$ the moisture content of hydrated water [%], $M_{dis}$ the moisture content of dissolved water [%], and finally $M_{total}$ as the total moisture content [%].

# 3. Results and discussion

Thermal conductivity data of the measured insulation fibreboards at different moisture contents, for the temperature range of -10°C to 60°C, are shown in Figure 2. The average equilibrium moisture contents after conditioning at 15%, 50%, 85% of RH were gravimetrically determined. Thermal conductivity increased as temperature and moisture content of the wood went up, as previously reported (Kühlmann, 1962). Yu et al. (2011) reported that the thermal conductivity is linearly proportional to the temperature, which confirms the own data.

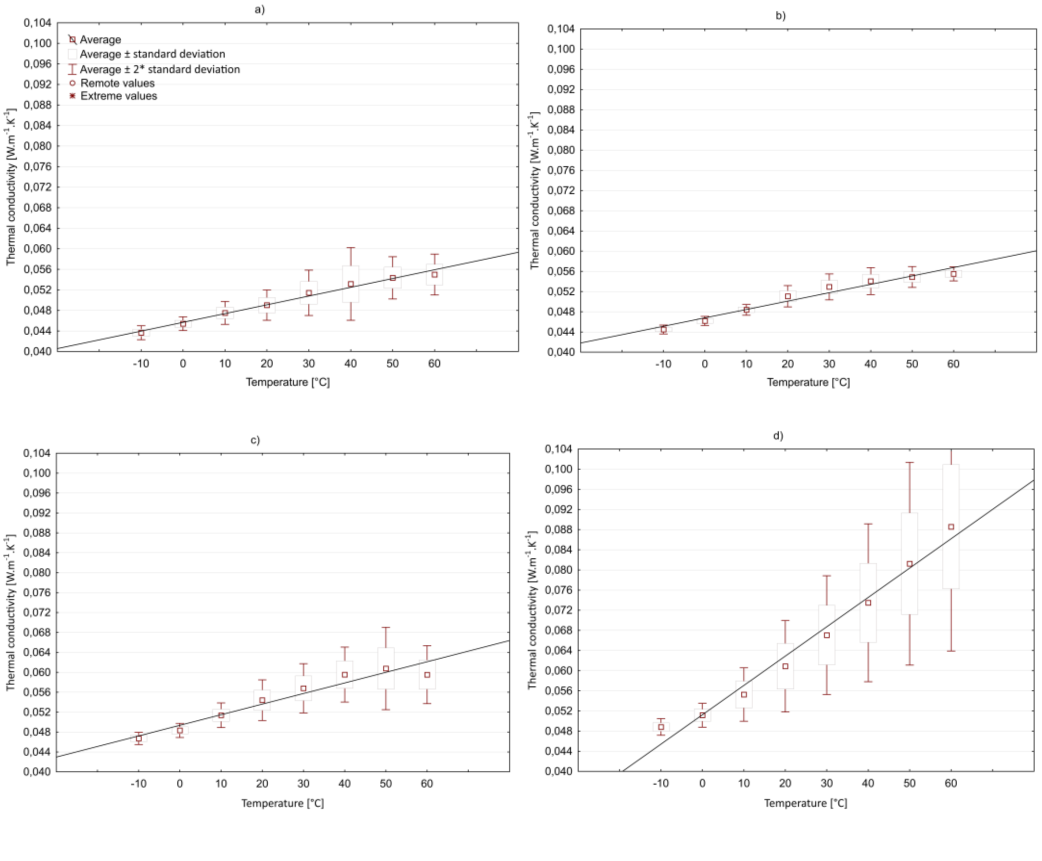



**Fig. 2** Insulation fibreboard thermal conductivity as related to temperature, at different moisture contents of the boards: a) oven dry, b) 2.58%, c) 7.41%, d) 14.29%.

Accuracy of the heatflow measurement was ±3%. The influence of the thin protective foils on thermal properties proofed to be negligible (<1%). A greater variability can be seen at higher temperatures and moisture contents, which may be caused by inner moisture transfer. Even though the overall change of MC is less than 0.3% during measurement, an inner translocation of moisture seems to be possible (Avramidis and Siau, 1987). This assumption is supported by the increased time at higher temperatures and moisture contents required to complete a single heatflow measurement. The heat transfer quantified by steady-state technique includes not only equivalent conduction-convection-radiation transfer but also latent heat transferred via moisture movement in the material. Application of the thermal gradient to a previously homogeneously moist fiberboard leads to a vapor pressure gradient in the material and hence to vapor diffusion and furthermore the transfer of vapor enthalpy during measurement. The heat flow due to moisture gradient is significant especially during the initial stages of the moisture redistribution process (Bomberg and Shirtliffe, 1978). Condensation occurred at the colder surfaces when conditioned at 85 % of RH leading to higher variability in measured thermal conductivity data. Increasing the MC increases the time required to reach steady-state conditions (Bomberg and Shirtliffe, 1978), which confirms our assumption. The final heat flow depends on the distribution of moisture in the material in a closed system (Rudtsch, 2000). The water content distribution is dependent on the temperature gradient. With lower temperature differences becomes the MC distribution rather uniform (Ikeda et al., 1980).

The conductivity values varied with moisture content, which is caused by water conduction. The higher the moisture content, the higher the thermal conductivity (Zhou et al., 2013). Thermal conductivity increased almost linearly with moisture content at a given temperature. Further, the higher the temperature, the bigger the differences were between conductivity values at oven-dry condition (increase of 12%) and at 14.2% of MC (increase of 61%). The relationship between thermal conductivity, temperature and MC of samples was established. The regression equation was found by fitting the data with a second order polynomial function ($R^2$= 0.958, formula 6).

$$\lambda = 0.0474 + 5.895e^{-4}w + 1.117e^{-4}T + 6.743e^{-5}w^2 - 1.226e^{-7}T^2 + 2.922e^{-5}wT \quad (6)$$

Mean moisture contents calculated for each RH during adsorption and desorption are shown in Table 1. Sorption hysteresis was observed as expected (Siau, 1984; Skaar, 1988; Požgaj et al., 1997); the hysteresis coefficient describing the ratio of measured EMCs in adsorption and desorption for every RH (mean values of 8 determinations) was as high as 0.77.

The experimental data allowed representing the hysteresis for the total RH range. Parameters describing the polynomial fitting curve are listed in Table 2. The goodness of fit ($R^2$) was 0.94 for adsorption, and 0.97 for desorption when using the H-H model. $K_1$ and $K_2$ are equilibrium constants representing fitting parameters of measured EMC values. The $K_2$ value was 0.75 for adsorption, and 0.59 for desorption, which indicates that the dissolved water shows lower activity than the liquid water. Total sorption as a composite of hydrated and dissolved water sorption is shown for adsorption as well as desorption (Figure 3). The H-H model separates the total moisture sorbed into its monomolecular (expressed in hydrated water) and polymolecular component (dissolved water) (Mantanis and Papadopoulos, 2010). Moisture content corresponding to the complete hydration was 5.56% for adsorption and 8.11% for desorption.

**Table 1.** Mean values for experimentally derived EMC at various levels of RH for insulation fibreboards (coefficient of variation in parentheses)

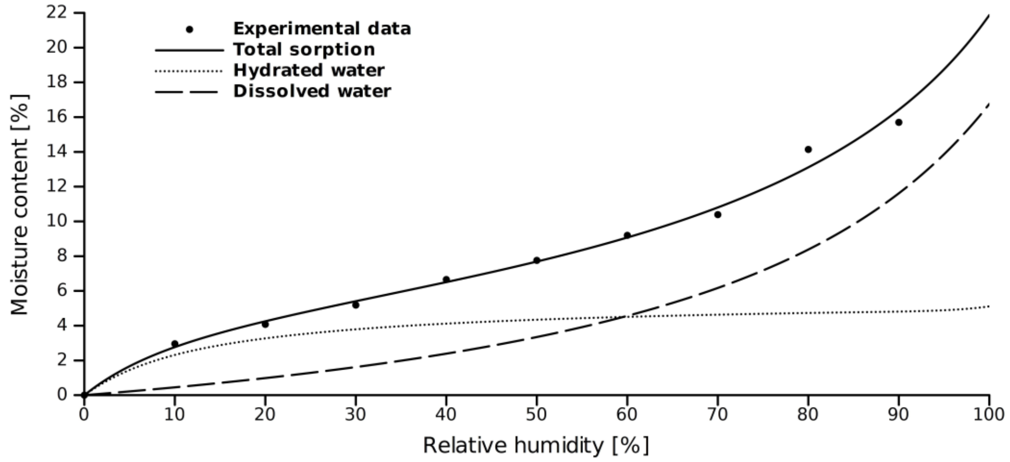
| **Relative air humidity [%]** | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 |
|---|---|---|---|---|---|---|---|---|
| | **Equilibrium moisture content [%]** | | | | | | | |
| **adsorption** | 3.0 (8.97) | 4.1 (6.24) | 5.2 (3.74) | 6.7 (3.52) | 7.8 (3.19) | 9.2 (2.48) | 10.4 (2.67) | 14.1 (2.88) |
| **desorption** | 5.3 (3.88) | 6.2 (4.58) | 7.6 (3.28) | 8.9 (2.57) | 10.2 (2.20) | 11.6 (5.26) | 13.2 (5.07) | 15.2 (14.12) |

**Table 2.** Constants calculated for the H-H adsorption isotherms

| **parameters** | **A** | **B** | **C** | **$K_1$** | **$K_2$** | **$R^2$** |
|---|---|---|---|---|---|---|
| adsorption | 2.28 | 14.56 | 12.23 | 9.49 | 0.75 | 0.94 |
| desorption | 1.10 | 11.03 | 6.89 | 17.93 | 0.59 | 0.97 |

Except of the H-H model, the Brunauer-Emmett-Teller (BET) theory or Dent model are often applied theories for sorption. These models use a multi-layered sorption concept, but they do not taking account partial cycles in terms of RH variations (Merakeb et al., 2009).

**a)**



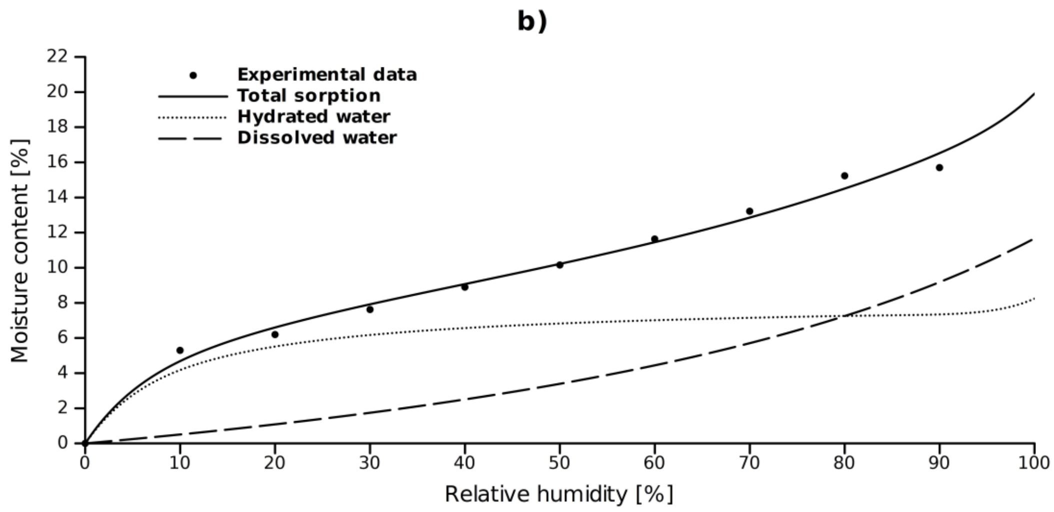



**Fig. 3** Sorption isotherms [(a) adsorption and (b) desorption] according to the H-H model at 20°C

# 4. Conclusions

A major motivation for this research was to obtain accurate parameters needed for numerical modeling of coupled moisture and heat transfer processes of insulation materials used in wooden buildings. A relationship between thermal conductivity, temperature and MC of samples was established, based on second order polynomial function fitting of experimental data. Increasing conductivity along with raising temperature and moisture content was again notified. The differences between conductivity values at oven-dry conditions and at 85% RH increased remarkably as temperature went up.

Mean values for experimentally derived EMC at various levels of RH for wood-based fibreboards were evaluated. Using the Haiwood-Horrobin (H-H) equation it was possible to separate total sorption into the hydrated and dissolved water sorption components. Increasing humidity leads to increased moisture contents. The thermal behaviour of fibreboards when installed as building façade insulation is remarkably affected by changes in temperature and moisture content. This finding is insufficiently known to manufacturers and builders. Accurate data on the thermal behaviour of insulation materials are needed, also to improve numerical modelling approaches to better optimize building envelopes.

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