STUDY ON THE MOISTURE MIGRATION WITHIN A HYGROSCOPIC THERMAL INSULATING MATERIAL FROM WOOD FIBRE DURING THE MEASUREMENT OF THERMAL CONDUCTIVITY

UNTERSUCHUNG ZUR FEUCHTEWANDERUNG BEI EINEM HYGROSOPISCHEN WÄRMEDÄMMSTOFF AUS HOLZFASERN WÄHREND DER MESSUNG DER WÄRMELEITFÄHIGKEIT

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SUMMARY

The present study is focused on the investigation of the mass transport of moisture, which is mobilised in a hygroscopic thermal insulation material made of wood fibres with a low moisture content by applying a temperature gradient.

In addition, the result on the equivalent thermal conductivity $\lambda_{10,23/50}$, obtained with the selected sample material after conditioning in the test climate 23°C and 50% RH, is discussed in the context of the regulation of annex D of EN 13171, which can be optionally applied for the determination of the nominal value of the thermal conductivity λ_D. The procedure of annex D allows to express λ_D on basis of the measured value of the equivalent thermal conductivity $\lambda_{10,tr}$, measured after previous drying of the sample at 70°C, with the aid of a special algorithm and with the inclusion of the current sorption moisture $\psi_{23/50}$.

ZUSAMMENFASSUNG

Die vorliegende Studie sollte bei einem hygroskopischen Wärmedämmstoff aus Holzfasern mit einem geringen Feuchtegehalt den Massentransport der Feuchte, der mit Hilfe des Anlegens eines Temperaturgefälles in Bewegung kommt, exemplarisch dargestellt werden.

Außerdem sollte das Ergebnis zur äquivalenten Wärmeleitfähigkeit $\lambda_{10,23/50}$, das mit dem ausgewählten Probenmaterial nach Konditionierung in dem Prüfklima 23°C und 50% r. F. erhalten wurde, im Kontext der Regelung des Anhangs D der EN 13171 diskutiert werden, der für die Festlegung des sogenannten Nennwerts der Wärmeleitfähigkeit λ_D optional anwendbar ist. Nach diesem Verfahren wird

der Messwert der äquivalenten Wärmeleitfähigkeit $\lambda_{10,tr}$, ermittelt nach vorangegangener Trocknung der Probe bei 70°C, mit Hilfe eines besonderen Algorithmus sowie unter Einbeziehung der aktuellen Sorptionsfeuchte $\psi_{23/50}$ beaufschlagt.

1. STEADY STATE HEAT TRANSFER IN A POROUS MATERIAL

There are several possible ways of heat transfer in a thermal insulating material. This is primarly owed to the fact, that the factory-made wood fibre boards (WF) for the insulation in buildings consist of wood particles, which create a felt-like anisotropic macrostructure with a big inner surface and many cavities of different sizes [Fig. 1].

Fig. 1: Cross-section of the WF-board

Furthermore, it depends on the aggregate state of the constituting elements, which defines the type of heat transfer.

According to the common approach of the steady state heat transfer [1, 2, 3] the following table No. 1 summarizes the physical processes in a moist thermal insulating material, which are taking place if it is placed in the field of a temperature gradient. The physical variable that describes the property of heat transfer of this kind of material is often referred to as equivalent of thermal conductivity [4].

Table 1: Possible processes of the different constituents in WF boards

Constituent	Phase	Process
Wood fibres	Solid	Heat conduction ($\lambda_{pinewood}$ = 18 $mWm^{-1}K^{-1}$)
Moisture	Liquid	Heat conduction (λ_{H2O} = 58 $mWm^{-1}K^{-1}$)
Air, moisture	Gaseous	Heat conduction ($\lambda_{air,10°C}$ = 0.025 $mWm^{-1}K^{-1}$)
Air, moisture	Gaseous	Mass transport by convection
Inner surfaces of solid	Solid	Radiation
Moisture	Liquid / gaseous	Phase changes (latent heat)
Gas molecules	Gaseous	Adsorption and desorption

The wood fibres of the board provide the conduction of heat, so do the liquid phase of moisture. Moreover, heat is also conducted by the molecules of air and of moisture. The presence of gases releases convection which is triggered by the temperature gradient. Therefore, the gaseous phase of moisture is capable to migrate by means of the general stream of convection. The surfaces of the solid particles and the gas molecules act as transmitter and receiver of the longwave radiation.

Two more physical processes - the phase change of moisture/liquid and the adsorption/desorption of gas molecules - occur during the measurement of the thermal resistance.

In this context it can be mentioned that the term “latent heat” is applied in this field for summarizing all the energies connected with the phase changes of a substance. In terms of specific gradients (energy per mass, kJ/kg) these are the phase change enthalpies of the respective phase transition (evaporation enthalpy, sublimation enthalpy).

The focus of the present study lies the qualitative and quantitative characterization of the mass transport of moisture going from warm to cold. A simple method is applied: cutting the test specimens into two halves across the direction of the heat flow and determining the mass of the halves before and after the measurement of thermal conductivity.

2. TYPE OF MATERIAL AND TEST PROCEDURE

Some general specific characteristics of the selected material of the wood fibre board are reported in Table 2. The board was manufactured by the so-called “dry processing”.

Table 2: General information on the wood fibre board chosen

Nominal thickness Density, dry Density, 23°C / 50 RH	60 mm 185 kg/m³ 193 kg/m³
Absorption of moisture μ23/50 ψ23/50	 0.076 kg/kg 0.014 m³/m³
DS(70,-) of thickness	2-3%

By purpose, the recommendation on the ratio of thickness / temperature difference [6] that should not fall below 10 mm per 1 K was not taken into account in order to increase the driving force behind the moisture migration.

Four test specimens, all sized 500 mm x 500 mm and of similar density, were selected out of a sample volume of 12 test pieces:

- test specimens No. 1 + No. 2 for the tests after drying
- test specimens No. 3 + No. 4 for the tests after conditioning in 23°C/50% RH.

The mass transport was examined with the sample pair No. 3 + No. 4 whose plates were each cut in two halves (No. 3.1, No. 3.2 and No. 4.1, No. 4.2) and afterwards conditioned in the test climate 23°C/50% RH until constant mass.

Immediately after finishing the drying at 70°C or after finishing the conditioning in the test climate 23°C and 50% RH, respectively, the test specimens were wrapped in a 20 µ PE-foil followed by putting in the test apparatus GHP [5]. Each half of the plate No. 3 or No. 4 was individually weighed before and after the measurement of the equivalent of thermal conductivity.

General information on the two-plate-apparatus and on the chosen test parameters can be taken from Table 3.

Table 3: General information on the equipment and on the parameter of measurement

Two-plate-apparatus GHP	mm	800 x 800
Metering area	mm	300 x 300
Inner guard section	mm	175
Outer guard section	mm	75
Compression on the sample	kPa	0.9 – 1.0
Mean temperature	°C	10
Temperature difference	K	11
Length of measuring time	h	42 – 47
Ratio of thickness / temperature difference	mm/K	5.4
Ambient conditions		
Room temperature	°C	22
Relative humidity of lab air	%	≈ 40 – 60

3. TEST RESULTS

The results of the measurements [5] on the equivalent of thermal conductivity are summarized in Table 4.

The mass change between whole and cut plates was 76 g on average between whole and cut plates. This explains the thickness reduction, which absolutely ranged from 1.6 mm to 1.8 mm.

As expected the measured value of the moist sample pair of both variations was clearly higher towards the measured value of the dry sample pair, 6% higher in the present case.

The difference of the measuring values of the sample pair variations at the same condition was 0.6% and 0.5%, respectively. It can be traced back to accidentally changed measurement conditions, to slightly varied parameters of conditioning and possibly to the presence of the separation layer.

Table 4: Equivalent of thermal conductivity

Sample pair	Sample variation and conditioning	Density [kg/m³]	Thickness [mm]	Equivalent of thermal conductivity [mWm^{-1}K^{-1}]
1 2	Whole test specimens Dried at 70 °C	184.7 184.5	58.7 58.7	43.20
1.1 1.2	Cut in 2 halves Dried again at 70 °C	---	57.1	43.46
2.1 2.2	Cut in 2 halves Dried again at 70 °C	---	56.9	
Difference between whole board and board cut into halve in percentage				0.60
Sample pair	Sample variation and conditioning	Density [kg/m³]	Thickness [mm]	Equivalent of thermal conductivity [mWm^{-1}K^{-1}]
3 4	Whole test specimens 23°C / 50% RH	192.6 193.5	60.6 60.4	45.81
3.1 3.2	Cut in 2 halves 23°C / 50% RH	---	59.0	46.05
4.1 4.2	Cut in 2 halves 23°C / 50% RH	---	58.8	
Difference between whole board and board cut into halve in percentage				0.52%

The Table 5 informs in detail on the changes in mass before and after the measurement runs.

The test specimens No. 3.1 + 3.2 and No. 4.1 + 4.2 absorbed moisture after conditioning in the climate of 23°C and 50% RH absolutely in an amount of 195 g and 198 g, respectively.

The masses of the dried sample pairs increased by 0.2% after the measurement. It may be attributed to the circumstance, that immediately after taking out the drying cabinet the test specimens were weighed in air before being cooled down.

In contrast, the mass change of the climate-conditioned whole test specimens can be neglected.

Table 5: Changes in mass before / after the measurement

Sample masses after drying at 70°C / --				
Variation	Sample	before [g]	after [g]	Mass change in mass percentage
1. measurement				
Sample pair,	1	2646	2652	+0.23
whole test specimens	2	2639	2644	+0.19
2. measurement				
Sample pair, test specimens	1.1 + 1.2	2574	2580	+0.23
cut in 2 halves	2.1 + 2.2	2560	2566	+0.23
Sample masses after conditioning at 23°C / 50% r.h.				
Variation	Sample	before in g	after in g	Mass change in mass percentage
1. measurement				
Sample pair,	3	2848	2849	+0.04
whole test specimens	4	2881	2880	+0.04
2. measurement				
Sample pair, cut	3.1 cold	1564	1572	+0.3
23°C / 50% RH	3.2 warm	1209	1201	-0.3
Total		2773	2773	
Sample pair, cut	4.1 warm	1205	1197	-0.3
23°C / 50% RH	4.2 cold	1600	1608	+0.3
Total		2805	2805	
Sample masses by drying at 70 °C / --				
Sample pair, cut	3.1 cold	1564	1454	7.6
23°C / 50% RH	3.2 warm	1209	1124	7.6
Total		2773	2578	7.6
Sample pair, cut	4.1 warm	1205	1119	7.7
23°C / 50% RH	4.2 cold	1600	1488	7.5
Total		2805	2607	7.6

The second measurements of the climate-conditioned test specimens showed a mass change in each layer of absolute 8 g on average (0.3% mass percentage), that must be attributed to the circumstance, that moisture had been migrated to the direction of cooler temperature during the test.

The total moisture content after drying at 70°C of the layers No. 3.1, No. 3.2, No. 4.1 and No. 4.2 was 7.6% by mass.

4. SUMMARY

According to the observation of the present study the following statements can be made:

(a) There are additional ways of the heat transfer in a moist material compared to a material without any stored moisture. It depends on the aggregate state of moisture and the type of transfer:

- heat conduction by the liquid phase (λ_{H2O} = 58 $mWm^{-1}K^{-1}$)
- heat conduction by the gaseous phase ($\lambda_{vapour,100°C}$ = 68 $mWm^{-1}K^{-1}$)
- mass transportation of moisture in the gaseous phase by convection

It is plausible that the liquid phase of the moisture is likely to make a clear contribution to the heat transmission by heat conduction, unlike the gaseous phase of moisture, which is assumed negligible.

Furthermore, the mass transport of the moisture could be proven in the present study. The share of 0.3% of the stored moisture was relocated from the “warm” slice into the “cold” slice within the two-day measurement period.

(b) In general, phase changes occur in the presence of moisture among the liquid and gaseous phases of water. These transitions (transition from liquid to gaseous) consume energy, called “latent heat”, which contributes to the heat flux density and which is included in the calculation of the equivalent of thermal conductivity.

(c) The following consideration is based on the calculated quantities, as listed below, which result from the evaluation on the different measurement data:

Variation	$\lambda_{equivalent}$ [$mWm^{-1}K^{-1}$]	Thickness [mm]	Heat Flux [W/m²]
Dry state	43.46	57.0	7.94
23°C/50% RH	46.05	58.9	8.62
Difference [%]	6.0	3.3	8.6

The calculation of the quantity $\lambda_{equivalent}$ includes the measured thickness d next to the heat flux q and the temperature difference ΔT. As can be seen, the increase in the value $\lambda_{10,23/50}$ is linked to the clear rise of both the thickness and the heat flux, which are related to the presence of moisture.

(d) The standard EN 13171 [6], annex D, describes an algorithm, which may optionally be used for the calculation of $\lambda_{10,23/50}$ on base of the test result $\lambda_{10,dried}$.

Applied to the current test result for $\lambda_{10,dry}$ the value $\lambda_{10,23/50} = 44.33$ mWm^{-1}K^{-1} was computed.

$\lambda_{10,dry}$ [mWm^{-1}K^{-1}]	Density [kg/m³]	Moisture [kg/kg]	[m³/m³]	f_ψ	$\lambda_{10,23/50}$ [mWm^{-1}K^{-1}]	Thickness [mm]
43.46	185	0.076	0.014	**1.4**	**44.33**	**57.0**

The moisture conversion coefficient $f_\psi = 1.4$ is to be used inside the density range from 40 kg/m³ to 250 kg/m³. The calculation is done by the following equation:

$\lambda_{10,23/50} = \lambda_{10,dry} \cdot \exp[f_\psi \cdot (\psi_{23/50} - \psi_{dry})$.

If the moisture conversion coefficient f_ψ is assumed as unknown, it could be determined with the available test results of $\lambda_{10,23/50}$ and $\lambda_{10,dry}$, as shown next.

$\lambda_{10,dry}$ [mWm^{-1}K^{-1}]	Density [kg/m³]	Moisture [kg/kg]	[m³/m³]	f_ψ	$\lambda_{10,23/50}$ [mWm^{-1}K^{-1}]	Thickness [mm]
43.46	185	0.076	0.014	**4.1**	**46.05**	**58.9**

The wide deviation among the f_ψ (standard) and f_ψ (study) can partly be explained by the assumption, that $f_\psi = 1.4$ was presumably derived from test results $\lambda_{10,23/50}$, whose determinations were done on base of the sample thickness related to the dry state.

In contrast to that the corresponding calculation leads to the coefficient $f_\psi = 1.8$ on the basis of $\lambda_{10,23/50} = 44.57$ mWm^{-1}K^{-1}, which resulted for the measured sample thickness related to the dry state.

$\lambda_{10,dry}$ [mWm^{-1}K^{-1}]	Density [kg/m³]	Moisture [kg/kg]	[m³/m³]	f_ψ	$\lambda_{10,23/50}$ [mWm^{-1}K^{-1}]	Thickness [mm]
43.46	185	0.076	0.014	**1.8**	**44.57**	**57.0**

More investigations are necessary to clarify the circumstances in order to remove this contradiction.

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