

Evaluation of changes in thermodiffusion properties of mineral wool resulting from treatment with water and re-drying

Zbigniew Perkowski*, Maciej Grygorowicz, and Kamil Jeż

Opole University of Technology, Faculty of Civil Engineering and Architecture, 45-061 Opole, Katowicka 48, Poland

Abstract. The work presents the formulation of inverse problem that allows to estimate the basic parameters describing coupled thermodiffusion of moisture in porous fibrous material and construction of the measuring stand in order to obtain the necessary data to carry out calculations for this purpose. This approach was used to evaluate the changes in the thermodiffusion properties of stone wool samples for the indoor applications that were treated with water and re-dried. In the mathematical model, one introduced a simplification that coupling in the thermodiffusion process is unilateral and includes only the influence of heat transport on moisture transport.

1 Introduction

Mineral wool is one of the basic materials for thermal insulation in civil engineering, but it is also used as a material for insulation of pipes, acoustic barriers, fire protection, artificial soil for plant breeding and core of sandwich panels. If the wool is properly protected against moisture, in the case of its using as thermal insulation in buildings envelopes, it combines very advantageous features: it is a very good thermal insulator, does not resist significantly moisture transport and hardly absorbs moist. Its properties are additionally improved from the applicative point of view by striving to produce a material with optimal entanglement and fibre orientation, the use of special anti-mold, anti-dusting, hydrophobic or hydrophilic admixtures. Particular attention should be paid to the hydrophobization or hydrophilization process from the point of view of controlling the thermodiffusion properties. For example, it leads to significant differences in the moisture accumulation capacity under the hygroscopic conditions shown in Fig. 1 in the light of variability in the sorption isotherms of mineral stone wool. It can be seen that the type of admixture used can be easily identified as a result of such testing. It can be also deduced that the use of hydrophobization reduces the possibility of moisture absorption in the lower part of hygroscopic range and is a beneficial phenomenon in typical operating conditions. However, if there is a relatively large moisture mass flux and no temperature gradient, it may unexpectedly lead to the precipitation of water drops in the space between the fibres of the wool and to its significant dampness. Such a

* Corresponding author: z.perkowski@po.opole.pl

situation may occur particularly in insulations inside buildings in the lower parts of insulation boards [1]. In this case, the use of hydrophilic additives will improve the transport of moisture and may avoid the described situation.

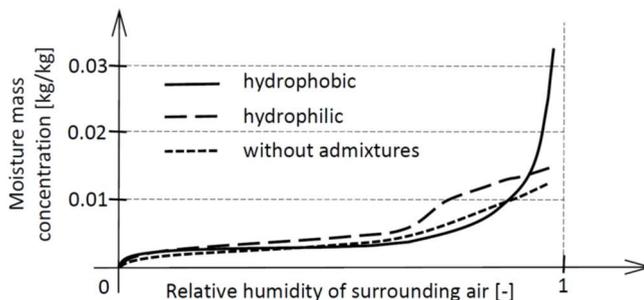


Fig. 1. A pictorial comparison of mineral stone wool sorption isotherms in the case of using hydrophobic and hydrophilic admixtures and without any admixtures (based on [1] for the wools with bulk density of $90\text{-}110\text{ kg/m}^3$ at temperature 23°C).

On the other hand, in the literature, one can find the first of all works oriented on the study of thermal conductivity of mineral wool, including its variability under the influence of temperature change [2], dampness [3, 4] and taking into account the influence of radiation [5, 6] or air convection [7]. Less often one can find works devoted also to detailed investigations of hygric features (sorption isotherms, parameters determining moisture diffusivity and liquid water transport) [1, 4]. There are basically no works devoted to direct determination of coefficients describing coupled thermodiffusion moisture transport in mineral wool with hydrophobic or hydrophilic properties and formulations of effective inverse problems for this purpose, despite the fact that the subject matter of coupled heat and moisture transport in porous materials is generally well described from theoretical point of view (e.g. [8-12]), as well as from the side of numerical modelling and experimental measurements both in homogeneous and complex (layered) systems (e.g. in [13-17] in the field of civil engineering problems). It is worth to note that in the case of experimental research, the multi-point measurement of temperature, relative air humidity in material pores and liquid water concentrations in building envelopes has become a standard.

In the light of the observations quoted, this work is devoted to the presentation of an effective and relatively quick way to evaluate the basic parameters describing the basic coupled thermodiffusion characteristics of mineral wool in the hygroscopic range. In the example of experimental research, samples of stone wool available in trade and dedicated for the internal applications were used. In the mathematical model of the process, a unilateral coupling the influence of heat transport on moisture transport was only included in order to simplify the considerations. In addition, due to the practical aspect of the problem, the effect of water saturation and re-drying on changes in the thermodiffusion wool parameters was examined because, in many situations as a result of improper storage at construction sites and inattention of contractors, the product is exposed for direct rain before or during inserting into building envelopes. In particular, for the wool impregnated with hydrophilic agents, it should be expected that this process will change the original favourable thermodiffusion characteristics, even though the wool has dried up again.

2 Materials and measuring stand

6 samples of mineral stone wool with density of $\sim 50\text{ kg/m}^3$ available in commercial were tested. The samples had dimensions of $\sim 100 \times 100 \times 75\text{ mm}$. According to the manufacturer, the wool with a declared thermal conductivity of 0.036 W/(m K) was dedicated to insulations

of internal partitions. 3 samples (marked as D1, D2, D3) were dried to constant weight at changing gradually temperature starting from 60°C and ending at 105°C within 2 weeks. The remaining 3 samples (marked as M1, M2, M3) were immersed in water for 24 hours in the temperature 22°C. After this time, they were removed from the water and left for one week in room conditions to allow the liquid water to drain freely from their pores. Then they were subjected to the same drying process as the first 3 ones. After this preliminary preparation of the samples, all of them were kept freely in a closed room (during a heating season) in which a measuring stand was situated, until their masses were stabilized. The stand made as part of the work [18] was used for the measurements, the scheme of which is shown in Fig. 2. After the mass stabilization, the samples of mineral wool together with a plate of acrylic glass with a thickness of ~ 21 mm and known thermal conductivity and diffusivity were placed individually in a sealed chamber with the same dimensions as the sample-plate system. The chamber was located in the middle between two 300 x 300 x 300 mm glass containers with water. The containers and chamber were thermally insulated using extruded polystyrene, and the chamber was protected by the exchange of moisture with the surrounding. The system includes combined sensors of temperature (thermocouple) and relative humidity (RH) of air on both sides of the sample and on the outside of the acrylic glass plate. The right measurement started when the indications of sensors were stabilized. Due to the method of preparation of samples, their initial temperature and relative humidity of the air in their pores corresponded to the ambient conditions prevailing in the room in which they were stored before insertion into the measurement system (respectively from 21°C to 26°C and from 34% to 45% depending on the sample). After inserting a sample into the test chamber, the water in the container from the side of the acrylic glass plate was heated with the electric heater within 3 h to a temperature of approximately 35°C. The temperature was kept constant due to the use of a thermostat for about the next 10 hours. The temperature and RH indications were archived every 10 s.

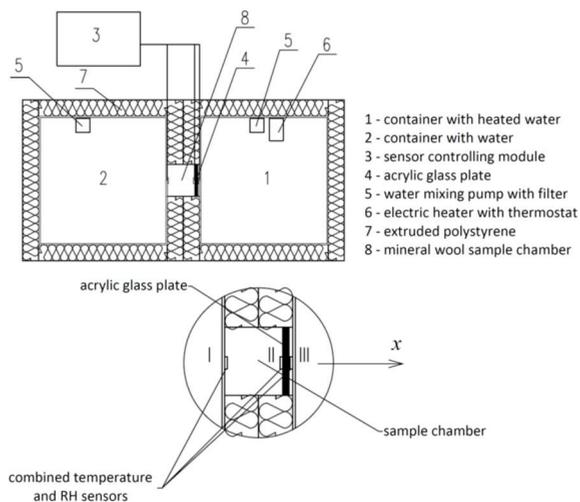


Fig. 2. A scheme of the measuring stand for the assessment of thermodiffusion properties of mineral wool [17].

Within a range of supplementary study, selected points of sorption isotherms were determined for the tested mineral wool at 22°C corresponding to RH of the air in the surrounding equal to 30, 40, 50, 70, 80% (by placing samples in the climatic chamber) and 98% (by placing samples in the desiccator above the water surface). In the case of sorption isotherms, the samples used for this purpose were also differentiated due to the methods of their preparation analogous to those for samples D1-D3 and M1-M3. The experimental

results obtained in the way described above were used to assess the thermodiffusion properties of the tested wool included in the applied mathematical model of the problem. They were presented and compared with the results of model calculations in paragraph 4.

3 Mathematical model

In order to describe theoretically the thermodiffusion process in the samples, its simplified model was used in which it was assumed that: no separate vapor and surface moisture transport is distinguished (which implies omission of local sources of mass and heat), coupling of the diffusion and thermal process may be considered approximately as unilateral (the heat flux affects the mass flux, and the impact of the mass flux on the heat flux is negligible), the sorption/desorption isotherm is approximated by a linear function, and material parameters are effectively treated as constant in the studied ranges of temperature and humidity, the material is isotropic, the heat and moisture transport is one-dimensional in the samples. Then, the equations describing the coupled heat and moisture transport and the initial-boundary conditions, corresponding to the conditions prevailing in the measurement system (i.e. in the sample and acrylic glass plate as shown in Fig. 2), can be generally expressed as:

$$\rho_w \frac{\partial C}{\partial t} = -\nabla \cdot \mathbf{j}, \quad \mathbf{j} = -\rho_w D_w \nabla C - \rho_w D_{Tw} \nabla T \quad \text{for } x \in (l_I, l_{II}) \quad (1)$$

$$\rho_w c_w \frac{\partial T}{\partial t} = -\nabla \cdot \mathbf{q}, \quad \mathbf{q} = -\lambda_w \nabla T \quad \text{for } x \in (l_I, l_{II}) \quad (2)$$

$$\rho_{ac} c_{ac} \frac{\partial T}{\partial t} = -\nabla \cdot \mathbf{q}, \quad \mathbf{q} = -\lambda_{ac} \nabla T \quad \text{for } x \in (l_{II}, l_{III}) \quad (3)$$

$$T(x, t = 0^+) = T_0, \quad T(x = l_I^+, t) = T_I, \quad T(x = l_{III}^-, t) = T_{III}, \quad \mathbf{q}(x = l_{II}^-, t) = \mathbf{q}(x = l_{II}^+, t) \quad (4)$$

$$C(t = 0^+, x) = C_0, \quad \mathbf{j}(x = l_I^+, t) = \mathbf{0}, \quad \mathbf{j}(x = l_{II}^-, t) = \mathbf{0} \quad (5)$$

where: T – temperature [K], T_0 – initial temperature [K], T_I and T_{III} – temperatures [K] measured by sensors I and III, respectively; C – moisture mass concentration [kg/kg], C_0 – initial moisture mass concentration [kg/kg], ρ – density of dry material [kg/m³], c – specific heat capacity [J/(kg K)], λ – thermal conductivity [W/(m K)], D – moisture diffusivity [m²/s], D_T – thermodiffusion coefficient [m²/(s K)] expressing influence of the heat transport on the moisture transport, \mathbf{q} – heat flux density vector [W/m²], \mathbf{j} – mass flux density vector [kg/(m² s)], $\mathbf{0}$ – zero vector, x – space variable [m], t – time variable [s], ∇ – nabla operator [1/m], w – subscript denoting the parameters for mineral wool, ac – subscript denoting the parameters for acrylic glass. The space coordinates of sensors I, II and III (marked in Fig. 2) are equal to l_I , l_{II} and l_{III} , respectively. The heat and mass flux density vectors for the formulated problem are of components:

$$\mathbf{q} = [q_x(x, t), 0, 0], \quad \mathbf{j} = [j_x(x, t), 0, 0] \quad (6)$$

According to the simplifying assumptions, the following relationship was assumed in the above system of equations between the moisture mass concentration C in the wool samples and the measured RH of the air in their pores:

$$\varphi = m_w C \quad (7)$$

where: φ – relative humidity of pore air [-], m_w – proportionality coefficient [-] between φ and C corresponding to the analysed variability of humidity.

In the analysed measurement system after switching on heating in container 1 (as denoted in Fig. 2) and re-stabilization of temperature indications in the sensors, it could be assumed that the heat transfer process is quasi-stationary. Thus, after about 13 hours from the start of measurements, the thermal conductivity λ_w of the sample was estimated in a simple way from equality occurring between the heat fluxes in the mineral wool sample and plate of acrylic glass with the known coefficient λ_{ac} assuming linear temperature distributions in individual layers of the system, which distributions were determined on the basis of indications of sensors I, II and III. Subsequently, knowing the thermal diffusivity of acrylic glass $a_w = \lambda_w / (\rho_w c_w)$, the thermal diffusivity of the sample $a_w = \lambda_w / (\rho_w c_w)$ was estimated by minimizing the function of the sum of square errors between the temperatures measured by sensor II and calculated according to the model at the point corresponding to the position of this sensor, i.e.:

$$\arg \min \left[\sum_i \left(T_{II}(t = t_i) - T(x = l_{II}^-, t = t_i, y) \right)^2 \right] = a_w \tag{8}$$

where: t_i – i -th measurement moment, y – variable corresponding to the a_w parameter in the initial-boundary problem defined by equations (2)-(4). After this step, D_w , D_{Tw} and m_w parameters were estimated by minimizing the function of the sum of square errors between the relative air humidity in the sample pores measured by sensors I and II, and calculated according to the model at the points corresponding to the positions of these sensors, i.e.:

$$\arg \min \left\{ \sum_i \left[\left(\varphi_I(t = t_i) - \varphi(x = l_I^+, t = t_i, y_1, y_2, y_3) \right)^2 + \left(\varphi_{II}(t = t_i) - \varphi(x = l_{II}^-, t = t_i, y_1, y_2, y_3) \right)^2 \right] \right\} = [D_w, D_{Tw}, m_w] \tag{9}$$

where: φ_I and φ_{II} – relative humidity [-] of the pore air measured by sensors I and II, respectively; y_1, y_2 and y_3 – variables corresponding to the D_w, D_{Tw} and m_w parameters, respectively, in the initial-boundary problem defined by equations (1)-(6). After obtaining the values of material parameters, the consistency of the measurement data and the model was each time evaluated by calculating the global relative errors of fitting the experimental and theoretical curves of temperature and relative humidity of air according to the following relations:

$$e_T = \sqrt{\frac{\sum_i \left(T_{II}(t_i) - T(l_{II}^-, t_i) \right)^2}{\sum_i T_{II}^2(t_i)}} \text{ for the estimated } a_w \tag{10}$$

$$e_D = \sqrt{\frac{\sum_i \left[\left(\varphi_I(t_i) - \varphi(l_I^+, t_i) \right)^2 + \left(\varphi_{II}(t_i) - \varphi(l_{II}^-, t_i) \right)^2 \right]}{\sum_i \left(\varphi_I^2(t_i) + \varphi_{II}^2(t_i) \right)}} \text{ for the estimated } D_w, D_{Tw} \text{ and } m_w \tag{11}$$

The solution of the presented initial-boundary problem was obtained using the Finite Difference Method, and the finding of the minimum error function using the Levenberg-

Marquardt algorithm. All the calculations have been carried out by the authors in the Matlab environment using own procedures written in the form of so-called m-files.

4 Results and discussion

The measured bulk densities and estimated material parameters using the calculation procedures described in the previous paragraph are summarized in Tables 1 and 2 for each of 6 samples D1-D3 and M1-M3. The average values of these quantities are also given. In turn, the measured points on the sorption isotherms of wool untreated by water and freely saturated by water during immersion and re-dried are shown in Fig. 3. Comparing them to the characteristic runs of sorption isotherms in the case of mineral wool treated by hydrophilic agents or not (Fig. 1), it can be concluded that the samples tested had hydrophilic properties, and after being saturated with water and re-dried, these properties were reduced because of possible partial leaching the agent, and/or its structural changes, and/or its chemical changes.

Table 1. Bulk density and estimated thermic parameters of stone wool samples with global errors of temperature curve fitting.

Type of sample curing	Sample	Density ρ_w [kg/m ³]	Coefficient of thermal conductivity λ_w [W/(m K)]	Thermal diffusivity a_w [m ² /s] x 10 ⁻⁷	Global error of temperature curve fitting according to formula (10) ϵ_T [-]
not immersed	D1	50.9	0.0341	7.15	0.0021
	D2	49.3	0.0344	6.18	0.0028
	D3	50.1	0.0343	6.20	0.0025
Mean value		50.1	0.0343	6.51	–
24 h water immersion and re-drying	M1	49.5	0.0364	9.77	0.0028
	M2	51.5	0.0391	9.17	0.0023
	M3	50.8	0.0313	11.92	0.0042
Mean value		50.6	0.0356	10.29	–

Table 2. Estimated hygric parameters with global errors of RH curve fitting.

Type of sample curing	Sample	Coefficient of moisture diffusion D_w [m ² /s] x 10 ⁻⁶	Thermo-diffusion coefficient D_{Tw} [m ² /(s K)] x 10 ⁻¹¹	Coefficient in formula (7) adopted for the sorption isotherm m_w [-] x 10 ⁻³	Global error of RH curve fitting according to formula (11) ϵ_D [-]
not immersed	D1	0.73	6.34	3.84	0.0156
	D2	0.71	6.24	4.35	0.0211
	D3	0.71	6.24	4.35	0.0182
Mean value		0.72	6.27	4.18	–
24 h water immersion and re-drying	M1	8.47	64.64	3.57	0.0120
	M2	7.12	59.28	3.89	0.0143
	M3	8.98	67.93	3.47	0.0148
Mean value		8.19	63.95	3.64	–

For the purpose of a qualitative comparison, these curves are presented together with the estimated dependencies which constitute their linear approximation found in the inverse

problem, which also may confirm this observation. In addition, the outputs shown in Tables 1-2 allow to deduce that the applied water immersion for this type of mineral wool after drying does not result in a change of its density, as well as in significant changes in its conductivity and thermal diffusivity. On the other hand, this process significantly increases the diffusion transport of moisture (increasing the value of D_w and D_{Tw} coefficients by an order of magnitude!). While the value of the diffusion coefficient D_w of the tested wool before the water immersion was lower than the typical values due to the admixtures used in its production, after this treatment and re-drying, the moisture diffusivity increased to the level commonly found in the literature. The following explanation of this fact can be proposed: in the first case, slower surface diffusion may be a dominant mechanism of moisture transport as a result of adsorption of water vapour on the wool fibres forced by the hydrophilic agent, and in the second due to the decrease in this effect, water vapour diffusion may be a dominant one as faster in this situation because of the relatively high porosity of wool. This hypothesis needs further studies taking into account possible changes of fibrous structure of the wool and from the point of view of the theory of thermodiffusion.

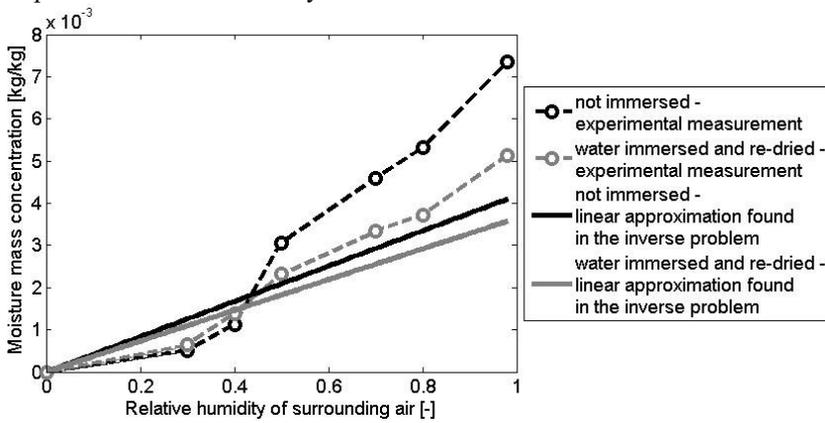


Fig. 3. Sorption isotherms of the stone wool not immersed and immersed in water and re-dried compared with their linear approximations found in the inverse problem.

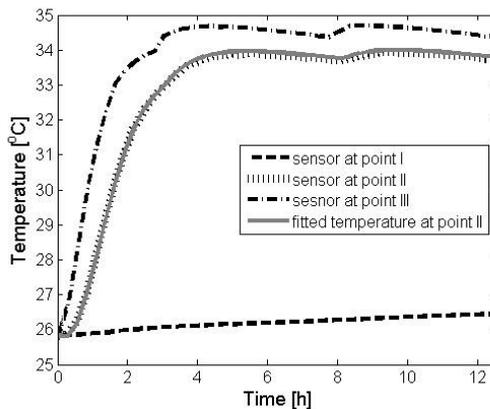


Fig. 4. Measured temperature time-courses by sensors I, II and III in sample D1. The temperature at sensor II is compared with the outcome of the adopted mathematical model for the estimated thermic parameters from Table 1.

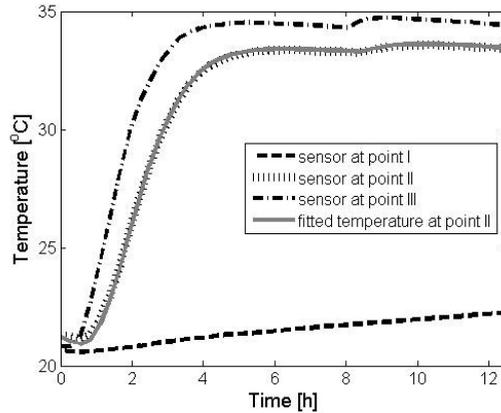


Fig. 5. Measured temperature time-courses by sensors I, II and III in sample M1. The temperature course at sensor II is compared with the outcome of the adopted mathematical model for the estimated thermic parameters from Table 1.

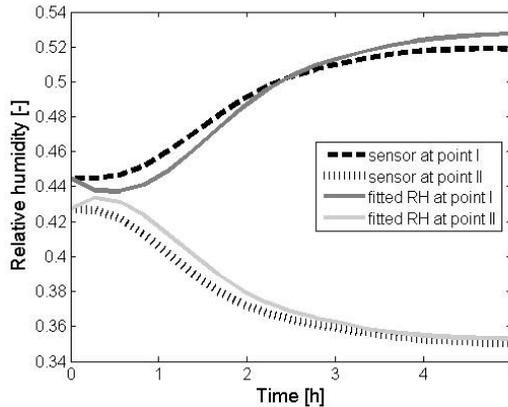


Fig. 6. Measured RH time-courses in the pore air by sensors I and II in sample D1. The relative humidity at sensors I and II is compared with the outcomes of the adopted mathematical model for the estimated thermo-hygric parameters from Tables 1-2.

There are also shown for example the temperatures for samples D1 and M1 measured by sensors I, II and III in Figs. 4 and 5 where, in addition, the temperature from sensor II is compared with the calculations based on the initial-boundary problem defined by equations (2)-(4) using the material parameters from Table 1. In this case, the temperature indications from sensors I and III were used as the boundary conditions of first-type according to relations (4). Similarly, the comparison of the relative humidity of the air in the pores of samples D1 and M1 measured by sensors I and II with those calculated in accordance with the mathematical model defined by relations (1)-(7) is shown in Figs. 6 and 7 for the material data from Tables 1-2. Taking into account the data from Figs. 4-5 and global errors in fitting the temperature curves from Table 1, it can be noticed that the assumption of unilateral coupling in the thermodiffusion model by considering only the impact of heat transport on mass transport is correct from the quantitative point of view in the analysed case.

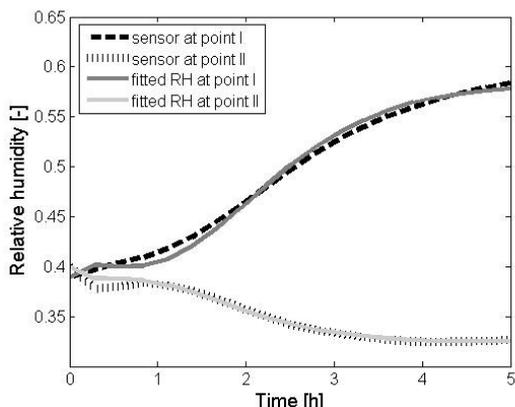


Fig. 7. Measured RH time-courses in the pore air at sensors I and II in sample M1. The relative humidity at sensors I and II is compared with the outcomes of the adopted mathematical model for the estimated thermo-hygric parameters from Tables 1-2.

In turn, the comparison of linear approximations of sorption isotherms with the experimental ones (Fig. 3) and the fit of the calculated and measured curves showing time-changes of relative humidity of the pore air in the samples (Figs. 6 and 7) suggest to use the more advanced descriptions in the diffusive part of the model to increase its accuracy.

5 Conclusions

The presented results allow to state that the presented measurement method enables quick determination of basic parameters describing coupled thermodiffusion in samples of fibrous materials. In addition, for the type of wool dedicated for indoor applications and tested within a framework of this work, the obtained results indicate that its exposure to direct atmospheric precipitation at construction sites can significantly change its thermodiffusion features originally given to it by manufactures. In this case, it should be emphasized that preservation of these properties is extremely important in operating conditions of mineral wool boards to avoid excessive moisture in them.

The authors would like to thank Prof. Mark Bomberg for valuable encouragement to build a measuring stand for thermodiffusion measurements of this kind.

References

1. M. Jiříčková, R. Černý, Effect of hydrophilic admixtures on moisture and heat transport and storage parameters of mineral wool, *Construction and Building Materials*, **20** (2006) 425–434
2. A.A. Abdou, I.M. Budaiwi, Comparison of thermal conductivity measurements of building insulation materials under various operating temperatures, *Journal of Building Physics*, **29**, 2 (2005) 171–184
3. M.C. Chyu, X. Zeng, L. Ye, Effect of underground water attack on the performance of mineral wool pipe insulation, *ASHRAE Transactions*, **104**, 2 (1998) 168–175
4. M. Jerman, R. Černý, Effect of moisture content on heat and moisture transport and storage properties of thermal insulation materials, *Energy and Buildings* **53** (2012) 39–46

5. F.M.B. Andersen, S. Dyrbøl, Modelling radiative heat transfer in fibrous materials: The use of Planck mean properties compared to spectral and flux-weighted properties, *Journal of Quantitative Spectroscopy & Radiative Transfer*, **60**, 4 (1998) 593–603
6. F.M.B. Andersen, S. Dyrbøl, Comparison of radiative heat transfer models in mineral wool at room temperature, *Radiative Transfer II*, 2nd International Symposium on Radiation Transfer, July 1997, Kusadasi, Turkey (1997) 607–619
7. S. Dyrbøl, S. Svendsen, A. Elmroth, Experimental investigation of the effect of natural convection on heat transfer in mineral wool, *Journal of Thermal Envelope and Building Science*, **26**, 2 (2002) 153–164
8. J. Kubik, Thermodiffusion flows in a solid with a dominant constituent, *Mitteilungen aus dem Institut für Mechanik, Ruhr-Universität Bochum*, **44**, Bochum (1985)
9. A.V. Luikov, Heat and mass transfer in capillary-porous bodies, *Advances in Heat Transfer*, Editors: T.F. Irvine, J.P. Hartnett, **1** (1964) 123–184
10. J.R. Philip, D.A. De Vries, Moisture movement in porous materials under temperature gradients; *Transactions, American Geophysical Union*, **38**, 2 (1957) 222–232
11. S. Whitaker, Simultaneous heat, mass, and momentum transfer in porous media: A theory of drying, *Advances in Heat Transfer*, Editors: J.P. Hartnett, T.F. Irvine, **13** (1977) 119–203
12. J. Wyrwał, A. Marynowicz, J. Świrska, On tensorial forms of thermodynamic potentials in mixtures theory, *International Journal of Solids and Structures*, **46**, 11–12 (2009) 2293–2297
13. M. Van Belleghem, M. Steeman, A. Willockx, A. Janssens, M. De Paepe, Benchmark experiments for moisture transfer modelling in air and porous materials, *Building and Environment*, **46** (2011) 884–898
14. Q. Li, J. Rao, P. Fazio, Development of HAM tool for building envelope analysis, *Building and Environment*, **44** (2009) 1065–1073
15. T. Ojanen, Moisture performance of mineral wool insulation products in highly insulated structures, 11th Nordic Symposium on Building Physics, June 2017, Trondheim, Norway, *Energy Procedia*, **132** (2017) 795–800
16. Z. Pavlík, R. Černý, Hygrothermal performance study of an innovative interior thermal insulation system, *Applied Thermal Engineering*, **29** (2009) 1941–1946
17. H.J. Steeman, M. Van Belleghem, A. Janssens, M. De Paepe, Coupled simulation of heat and moisture transport in air and porous materials for the assessment of moisture related damage, *Building and Environment*, **44** (2009) 2176–2184
18. M. Grygorowicz, K. Jeż, Badania przepływów wilgoci i ciepła w wybranych, porowatych materiałach budowlanych – budowa stanowiska pomiarowego, Diploma thesis, Opole University of Technology, July 2017, Opole (2017)