Energy & Buildings 214 (2020) 109902

Contents lists available at ScienceDirect

Energy & Buildings

journal homepage: www.elsevier.com/locate/enbuild

Investigation of the thermal insulation performance of fibrous aerogel samples under various hygrothermal environment: Laboratory tests completed with calculations and theory

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ARTICLE INFO

Article history:
Received 18 November 2019
Revised 23 February 2020
Accepted 24 February 2020
Available online 25 February 2020

Keywords:
Fibrous aerogel
Climatic conditions
Thermal conductivity
Insulation stability

ABSTRACT

Insulation materials are mainly porous or fibrous materials. Therefore, the presence of moisture can easily cause problems inside the materials, and in the whole building structure. For correct calculations of heat and moisture transfer problems in building applications, practitioners need design values. Design thermal values are deduced and calculated from declared values which are reached from laboratory measurements. This is the case for both insulation and building materials. If the design environments are different from those where the declared values should be used, the data have to be changed to the relevant conditions. There are standards giving suggestions on how to calculate the design values of thermal insulation materials, however, their database and tables are insufficient regarding the values of the super insulation materials. In this paper, a calculation method will be presented so as to specify the design thermal conductivities of a glass fiber-reinforced aerogel. The calculation method is based on measurement results, where the lambda values were measured treating the samples in a humid environment. As a result, the moisture conversion coefficient for the thermal conductivities is obtained after measuring the humid thermal conductivities of materials. Moreover, a new calculation method will also be presented to estimate the vapor absorption coefficient from humidity measurements. Furthermore, the effects of ice and freeze on the thermal conductivities of the aerogel samples are characterized, too. The thermal conductivities were measured in a Holometrix type heat flow meter, while for the wetting a Venticell 111 type drying apparatus and a Climacell 11 climatic chamber were applied. Moreover, the cooling treatment was executed in a freezing room. In addition, new theory for the thermal conductivity was given, for moist/frost insulation materials.

1. Introduction

In the European Union, the energy use of buildings counts for about 20 to 40% of the entire energy consumption [1,2,3]. The above-mentioned energy use goes together with about 30% greenhouse gas emission. One way to reduce these unwanted phenomena is the application of thermal insulation materials on the walls. The market is full of insulation materials, but these days the application of different types of silica aerogel is very promising. It is said that the commercially available ones have excellent thermal conductivity values with approximately 0.017 W/mK. They are porous materials having small density and with pores and cells on the nanoscale. Due to their fibrous structure, moisture might have a substantial reduction effect in the thermal resistance. The effect of humidity and moisture in the properties of this material is widely discussed by other papers. However, none of them goes deeper into the procedures [4,5,6,7,8,9,10]. In contrast, in this article, and the exact use of the measured values will be presented, and new calculation methods will be shown in order to find the design thermal conductivity of aerogel. Moreover, previous publications do not take into account the effects of both freezing (freeze-thaw cycles) and ice (moisture inside the material in solid phase) in the thermal conductivity. This paper will also show thermal conductivity measurement results after cooling samples on −15 °C for days, and cooling them in the humid state (after wetting). Due to the necessity of the insulation of buildings in cold climates, the characterization of the samples in these conditions is also necessary. It was previously presented that aerogel based materials can be efficient tools for thermal refurbishments of historic buildings [11,12,13]. Historical buildings are typical buildings where insulation with great thickness cannot be used, therefore materials with

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https://doi.org/10.1016/j.enbuild.2020.109902

very low thermal conductivity should be used. Several historical buildings can be found in the cold climate, too [14,15]. For this reason it is unavoidable to talk about and investigate the behavior of the aerogel samples in a cold environment [16,17,18]. The main goals of the article are to give new measurement results and present supplement of a standard widely used by researchers and designers. The paper serves new results of thermal and moisture related investigations of fiber-reinforced aerogel blankets is presented. As a result, the paper presents: suggestion for a new moisture related coefficient; new moisture conversion coefficients; new results as an effect of water; new method for investigating the effect of the frost; new theory for the thermal conductivity of moist insulations; materials testing to understand the background of sorption.

1.1. Water in materials

Insulation materials are usually porous or fibrous materials, therefore the presence of water can definitely cause problems inside the materials and within the entire building structure. In the sorption technique two types of the phases of moisture can be defined: the vapor phase and its transports through the pores. After condensation inside the material liquid water forms. Materials contain water in normal quantity what is the equilibrium moisture contents of the material at 23 °C temperature and 50% relative humidity. Over the normal quantity the moisture can cause undesirable changes. One other form of water can be its solid phase (ice). The vapor phase has minimal effect only with a slight decreasing consequence in the thermal resistance. However, the liquid phase can cause very harmful changes by increasing the thermal conductivity, moreover it can make chemical changes, too. The presence of ice can cause changes in the materials through the expansion of the volume. The building materials are mostly forms in three types: 1) Materials where between the solid particles and the water molecules only chemical bonds can be formed (e.g.: metals), where moisture up-taking only can happen through with adsorption at the solid surface. 2) Materials having closed cell structures: they can take up water only with adsorption (e.g. a plastic foam material with high compressive stress), but small amount of transport inside the pores can happen. 3) Open celled materials. Three different type of interrelation with water can be defined. 1. chemical bonds which, can only be broken by heat treatment, 2. physical-chemical bonds are where adsorption can happen on the surface of the solid material. Besides sorption, adsorption can be found, too [19].

1.1.1. Effects of water and vapor

The humidity effects can be divided into the following sets:

- water and its effects,
- vapor/gas phase and its effects.

Moisture from the wrong operation can be appear as the incorrect maintenance of the buildings. Condensation inside both the structure and the material can cause mildew growth [19].

1.1.2. Sorption isotherms

One method to analyze the specific surface area and the porosity of materials is to specify the sorption isotherms. The frequently applied two sorption isotherm graphs are the Langmuir and the BET, ones. The mentioned two characteristics are the most vital ones. Till about 40% in the relative humidity both curves show a square root of the time type functions, this means that during water up-taking firstly the adsorption process takes place on the surface. Over this relative humidity value, the BET isotherm represents a continuous increase, while the Langmuir type shows a continuous equilibrium moisture content [5,19,20,21,22].

1.1.3. Moisture absorption and kinetic curves

The water absorption coefficient "A_w" value of a material succeeds the capillary transport of the liquid. "A_w" values are defined as (Eq. (1)); as the ratio of the water content (m_{wet}-m_{dry}) in kg, (where m_{wet} and m_{dry} are the moist and dry masses of the samples), (A) is the area as well as the square root of the wetting time (t) in second. If we execute this experiment in a climatic chamber under a fixed temperature and relative humidity pair we can reach a value similar to "A_w" but for the vapor state, it can be defined as "A_v", where the "v" in the index designates the presence of vapor.

$$A_v = \left(m_{wet} - m_{dry}\right) / \left(A * t^{1/2}\right) \tag{1}$$

[19,23,24,25,26].

1.1.4. A calculation method of the moisture conversion factor

In this section, I would specify the method to reach the design thermal value of the glass fiber-reinforced aerogel. The design thermal conductivity of insulation material at specific environmental conditions (external or internal) represents its performance in use [27,28]. The calculation method of both the declared and the designed values of thermal conductivity is given in ISO 10456 standard, however, the data of the table is insufficient and the data referring to the aerogel are missing. This standard provides the calculation method as the following: Transformations of thermal conductivity values from one set of circumstances (λ_1) to another set of circumstances (λ_2) can be done by using the expressions below (conversion of moisture): F_m is a factor, and it is used for the conversion, moreover, it is determined in the function of moisture content as follows:

a) Transformation mass by mass:

$$F_m = e^{fu(u_2 - u_1)} \tag{2}$$

where f_u is the moisture conversion coefficient, u_1 and u_2 are the moisture contents in kg/kg of the first and the second sets of circumstances respectively.

$$\lambda_2 = \lambda_1 * e^{fu(u_2 - u_1)} \tag{3}$$

and λ_1 and λ_2 are the thermal conductivities belonging to the first and the second sets of conditions.

a) Transformation volume by volume:

where f_ψ is the moisture conversion coefficient, ψ_1 and ψ_2 are the moisture contents in m^3/m^3 of the first and the second sets of circumstances respectively.

$$F_m = e^{f\psi(\psi_2 - \psi_1)} \tag{4}$$

$$\lambda_2 = \lambda_1 \cdot e^{f\psi(\psi_2 - \psi_1)} \tag{5}$$

By using Eqs. (2) to (5) one can calculate the thermal conductivities with given moisture content. There are two possibilities for ψ_1, u_1 with λ_1 as follows:

ψ_1, u_1 are the moisture contents and can be equal to 0, if the samples are dried to changeless weight, in this case λ_1 is the thermal conductivity of the purely dried sample. Another possibility is if one uses the equilibrium moisture contents after treating the samples at 23 °C and 50% in a climatic chamber and measures their thermal conductivity. For some materials the data are given in the ISO 10456 standard, however, for aerogel, they are missing. In this paper, we will present new f_u and f_ψ values belonging to the fiber aerogel samples. If needed, one can recalculate the two definitions of moisture content according to the following equation:

$$\psi = u * (\rho_{ins} / \rho_{water}) \tag{6}$$

where ρ_{ins} and ρ_{water} are the densities of the insulation material and the water respectively.

Table 1
Material properties [6, 30].

Experiment	As-received sample
Sorption isotherm curve, BET type	Type II, macroporous adsorbents with strong affinities
Optical microscope (M = 20x)	fibers with grains
Scanning Electron Microscope, (M = 100x)	fibers with grainsSi, O, Al, C
X-ray diffraction - 2Θ, (°)	Amorphous SiO_2 peak at 22,5–27
Differential Scanning Calorimetry, specific heat capacity, (J/(kg K))	1000
Raman spectroscopy	Amorphous SiO_2, OH and organic groups

2. Materials and methods

2.1. The used samples

The tested material was Spaceloft type glass fiber-reinforced aerogel. The properties of the materials can be found both in its declaration sheet and in the latest papers of the authors. The elementary contaminants of the material are Carbon, Oxygen, Alumina, Silicon, and Calcium. The main components are the amorphous SiO_2 and Polyethylene Terephthalate embedded in the fibrous glass [5,6,29]. The sample is prepared by the manufacturer through a sol-gel process.

Mass map of the tested sample carried out by Secondary Neutral Mass Spectrometry (SNMS) can be seen on the following graph:

Scanning Electron Microscopy is an efficient method to determine the distribution of atomic content s of materials, as well as the microscopic structure of the material. The contaminants are analyzed in a mass spectrometer after post ionization. From the graph (see Fig. 2.) above one can see the main atomic components of the samples: C, O, Al and Si [6].

In some recent papers the authors represented the material properties of the tested sample, which we would summarize in Table 1:

Hypothesis for the measurements concluded from Table 1:

- Due to the fibrous structure and the presence of the OH-roots as well as organic groups, the moisture up-taking capacity must be high.
- Due to Amorphous SiO_2 content, good thermal insulation capability should be expected.

2.2. Wetting measurements

The measurement possibilities are clearly written in our latest papers. For the measurement of the moisture/water up-taking phenomenon of materials three apparatus should be used together. A dryer or a desiccator (eg: Venticell 111), a climatic chamber (Climacell 111) and a (milligram preciseness) weighing scale. Before wetting the samples they must be dried to constant mass. After desiccating, probes should be placed in a humidity (incubator) chamber. In our context, it is a Climacell 111 instrument. This apparatus is a laboratory incubator where the homogenous environment can be created. After both desiccating and curing the mass of the samples has to be registered with the balance. Wetting experiments should be divided into two parts. One part is when we would like the take up the sample's sorption isotherm graph (equilibrium moisture contents vs. relative humidity), while the other one when we investigate the time dependence of the moisture uptake.

2.2.1. Registering the sorption isotherms

In order to characterize the sorption isotherm curves of the solid materials the ISO 12571: 2013 standard should be used [26]. The two most important sorption isotherm shapes were previously discussed. As it was well presented in some latest papers the following steps should be done in order to register the sorption isotherms: 1. the materials must be dried to changeless weight, 2. the dried samples should be wetted to an equilibrium state in a humidity schamber at a fixed temperature (usually 23 °C) under at least five relative humidity values from 20 to 90% with at least 10% steps. In our case 35, 50, 65, 80 and 90% relative humidity values were applied. For this the moisture content can be found as:

$$u(kg/kg)=\left(\left(m_{wet}-m_{dry}\right)/m_{dry}\right) \quad (7)$$

2.2.2. Time dependent humidity treatment (kinetic)

If one fixes the temperature beside the relative humidity in a humidity chamber as well wets the samples for different times, the shape of the curves might become a shape with a square-root type curve. It starts from the origin and lasts until the equilibrium moisture content.

2.2.3. Freeze-thaw cycles and effect of ice (frost experiments)

Materials are subjected to temperature change as dilatation or contraction, which can be the source of mechanical and physical modifications; and generate internal stresses inside with about 9% when it freezes (ice forms). Therefore, the repetitive freeze-thaw cycles might cause measurable changes in the building or material structure. As it is well known, very cold weather, frost and ice can cause cracks inside the materials through expansion. For the investigation of the effects of frost and ice two experimental rows were executed on the aerogel samples, too. Firstly, the aerogel sample was treated in a cold chamber at −15 °C for weeks, and the thermal conductivity was measured. Than the aerogel samples were wetted in the climatic chamber until they reached the equilibrium moisture content – surely, after drying in the Venticell apparatus - and the wet samples were placed in the cold chamber and were treated at −15 °C for one day. Afterward, the thermal conductivity of the materials containing ice was measured. The samples were treated in the humidity chamber at 23 °C and under 35, 50, 65, 80 and 90% relative humidity.

2.2.4. Thermal conductivity measurements

In order to estimate the thermal insulation capability of a material, it's thermal conductivity should be measured in this case with a heat flow meter (Holometrix Lambda 2000). The experiments in order to measure the lambda values the rules of the EN ISO 12664:2001 standard were followed in the experiments. The measurement details, the mechanisms of the equipment, as well as its reproducibility and accuracy, are fully presented in the latest papers of the author. For each case we measured the thermal conductivity for five times and in the figures these mean values and the standard deviations (absolute ± deviations) are given. By the manufacturer with this instrument about 5% accuracy can be reached [5,6,23,28].

3. Results and discussion

3.1. Results of the vapor absorption measurements

The method presented in Fig. 1 and Eq. (1) was used to specify the vapor absorption coefficient of the aerogel samples. By fitting

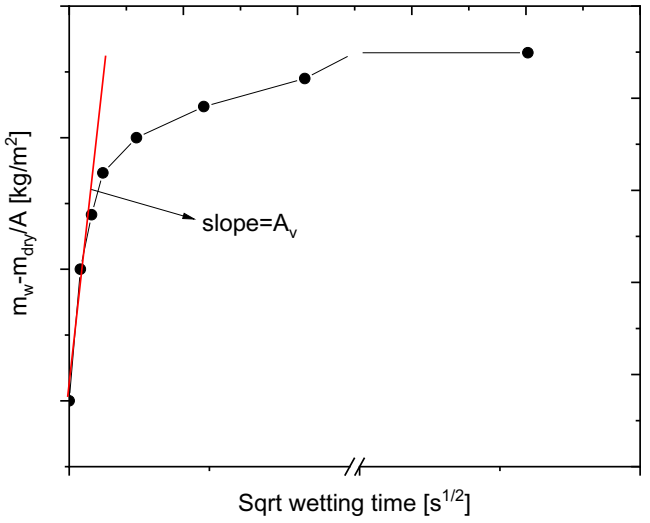

Fig. 1. The kinetic curve.

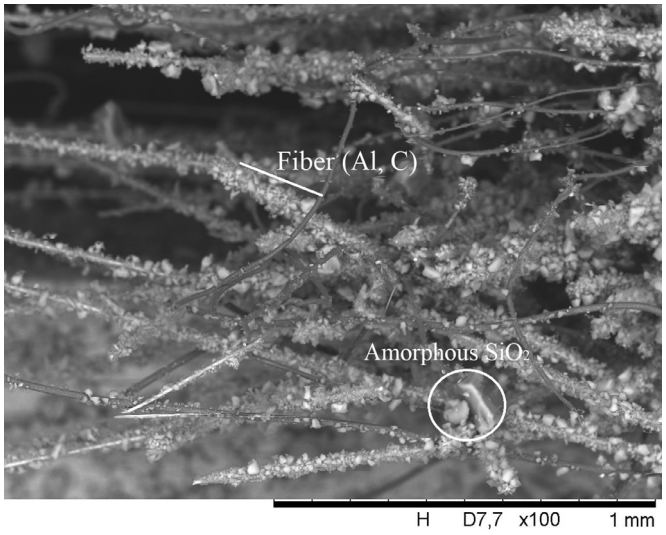

Fig. 2. The SEM test results.

the first strongly increasing part of the kinetic curves presented on the graphs below (Fig. 3a–e) we can reach the "A^v" values, in our case at 23 °C. These values are evaluated before the steady (equilibrium) stage. From Fig.3a –e we can see that the "A_v" is increasing with the rising relative humidity because it represents higher partial pressure. One can further observe that the regression (R^2) values of the linear fits are at least 0.94 for each.

By plotting the reached 'A_v' values reached from Fig. 3a – e in the function of the partial pressure (calculated from the relative humidity) we reached a linearly increasing function, with 99% regression. The slope of the linear fit is approximately 1.1×10^{-7} (see Fig. 4).

3.2. Moisture conversion coefficient of the aerogel

In ISO 10456 standard one can find the calculation method for the conversion of the thermal conductivity of materials in function of the moisture content. It is available both for mass/mass and volume/volume conversions. But the input data for the materials are few, these are only available for about 3–4 insulation materials [27]. Authors in a report gave some input parameters for some other materials, but they skipped the fibrous aerogel, too [32]. For the completion of the database, based on measurement results input parameters for the moisture conversion were calculated. Values both for mass/mass and for volume/volume were defined. If one knows the thermal conductivity of a dried as well as a wetted sample having equilibrium moisture content by using Eq. (2)–(6) the moisture conversion coefficients can be found. The standard presents two methods for the calculation of both the kg/kg and the m^3/m^3 conversions. In the first one the initial parameter is the thermal conductivity of a purely dried sample, and the other when the starting point is the thermal conductivity of the materials in equilibrium state wetted at 23 °C and 50%. Furthermore, if one measures the thermal conductivities having equilibrium moisture contents after wetting at different relative humidities (65, 80 and 90%), functions can be found. These measurement results are presented in Fig. 5a and b as well as with the results of the calculations.

By using the above-mentioned method for reaching the moisture conversion coefficient (mass/mass) $f_{u,dry}$ in dry state and for the pre-wetted state $f_{u,23,50}$ for the aerogel, figures were plotted to represent the measured values (see Fig. 5a and b). From the solution of Eq. (2) by fitting the measurement results, thermal conductivities in the function of moisture content can be reached. From the transformation, the moisture conversion factor can be deduced. Both the measured and the calculated thermal conductivities are indicated in the figures, while the coefficients are collected in Table 2.

The calculations were executed for the conversion in volume/volume state. For this using Eq. (6), the moisture contents mass/mass were transformed to m^3/m^3. Besides the presentation of the results in Fig. 6a and b, the results are also highlighted in Table 2.

Table 1 gives data for the completion of Table 4 in ISO 10456 standard by giving measured values for the aerogel. It represents the design values of the most important parameters e.g.: specific heat capacity and information on moisture content as well as the conversion factor. The moisture content of the material is given in equilibrium with air at 23 °C and relative humidity of 50% and 80%.

This table could be a completion as well to Table 4 of ISO 10456 standard. All the required data for this sample are highlighted. These input parameters should be very useful for planners, designers, and scientists in order to know the behavior of this material in different humid environments.

3.3. Effect of the freezing in the thermal conductivity of insulations

In order to see the possible effects of frost as well as ice in the thermal conductivity of the aerogel samples two different measurement rows were done additionally independently from the results presented above. One of them was kinetic treating of the initially dried aerogel sample in a cold chamber for weeks. The temperature, as well as the relative humidity in the freezing chamber, was fixed to −15 °C and 60% respectively. The temperature was chosen as the lowest thermal design temperature in this climatic area. and the sample was kept in the freezing chamber for different days in a row. With interrupting the freezing on designated days (1, 4, 8, 11, 18 and 25) the thermal conductivity was measured. In every cases 5 thermal conductivities were measured and their mean values and absolute deviances are given. The measurement results can be seen in the following figure. This measurement series could well simulate freeze-thaw effects. Interestingly, after the long-term freezing of the samples, the thermal conductivity remained constant (see Fig. 7).

Besides, the measurement results presented in Section 3.2. and Fig. 5a where, thermal conductivities of the samples were measured after drying them to changeless weight and they wetted them in the climatic chamber (Climacell) for one day at 23 °C and for 35, 50, 65, 80 and 90%. without freezing, one other experimen-

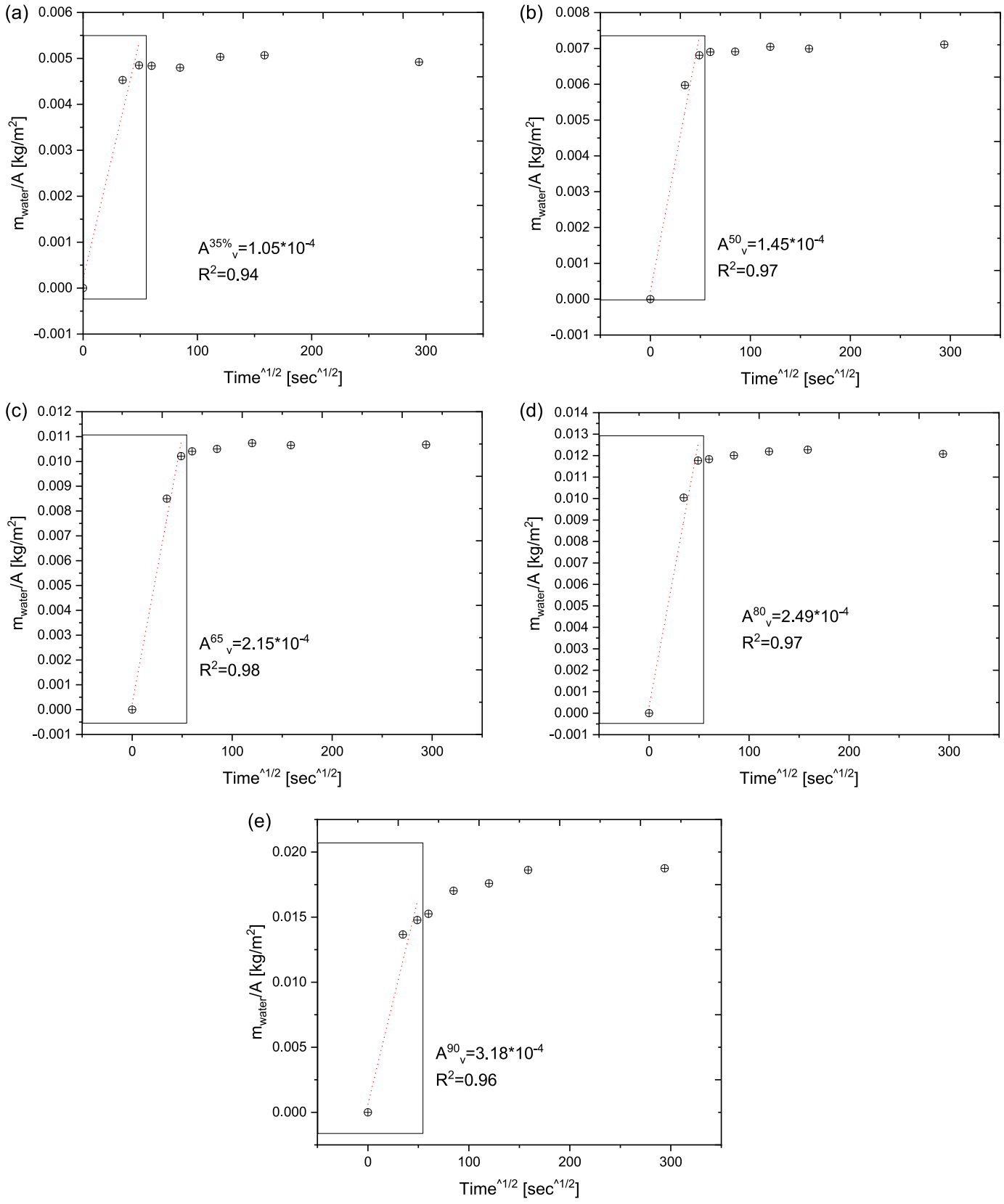

Fig. 3. (a) The wetting profile at 35% relative humidity. (b) The wetting profile at 50% relative humidity. (c) The wetting profile at 65% relative humidity. (d) The wetting profile at 80% relative humidity. (e) The wetting profile at 90% relative humidity.

Table 2
The moisture conversion coefficients for aerogel.

		Moisture content at 23 °C, 50% RH		Moisture content at 23 °C, 80% RH		Moisture conversion coefficient				
	Density [kg/m³]	u, [kg/kg]	ψ, [m³/m³]	u, [kg/kg]	ψ [m³/m³]	f_u; dry	f_u; 23 °C, 50%	ψ; dry	ψ; 23 °C, 50%	Specific heat capacity at 30 °C [J/kgK]
SL aerogel	156	0.015	0.0023	0.0225	0.0035	5.2	8	33	50	890

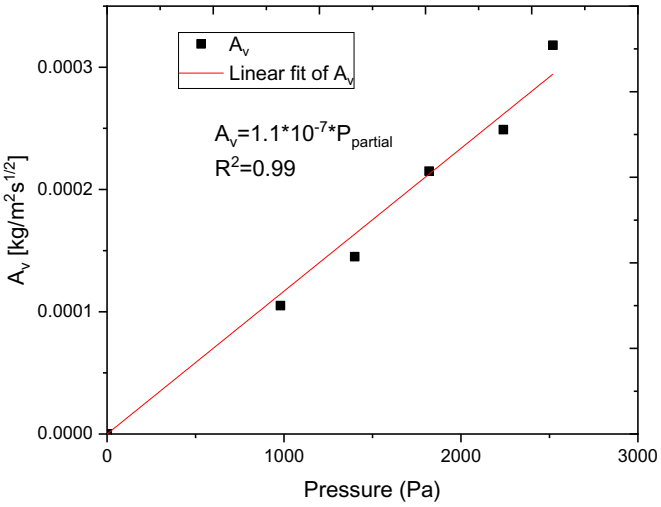

Fig. 4. The dependency of the 'A_v' values on the relative humidity.

tal row was executed, too. There, the wetting process was the same but after the wetting process they were frozen in the cold chamber at −15 °C and 60% relative humidity. After the freezing process their thermal conductivity was measured, too. (freezing) The percental changes of the thermal conductivities were calculated and were plotted in the function of the moisture content (no freezing) and for the frozen samples their changes in the thermal conductivity were plotted in the function of moisture + ice content.

In the "freezing" case the dried samples were wetted in the climatic chamber at 23 °C and for 35, 50, 65, 80 and 90% reaching the equilibrium moisture contents. But, after the wetting, each sample was placed in the freezing chamber at −15 °C for 1 day. After the freezing, their thermal conductivities were measured. Both their moist mass and their frozen mass were registered. The results are presented below, see Fig. 8., where the percentile change in the measured thermal conductivities is presented after wetting and freezing in the function of the moisture content before calculated from Fig. 5a ('no freezing') and after freezing. Here has to be mentioned that the measurement rows were separated and for both rows new samples were used.

For the comparison of the measurement results with those presented in Section 3.2 Fig. 8 was created. We can conclude that the percentile change in the thermal conductivity is greater for the changes belonging to the values after freezing. The reason for this is the following. The moisture content for the case of 'No freezing' was calculated by using Eq. (7), while the moisture content after freezing was calculated from the downer equation:

$$u_{frost}(kg/kg\%) = \left(\left(m_{frost} - m_{dry}\right)/m_{dry}\right) * 100 \quad (8)$$

Here has to be mentioned that for the initial state the frost moisture content was greater than zero, due to the mass change of the dried sample after freezing. Therefore, the initial moisture content here was 1.5%. Furthermore, the measured thermal conductivity belonging to this value was greater than the value measured for the purely dried sample's thermal conductivity, since the graph starts from 2% change. The highest change in the thermal conductivity is about 25% after freezing the moist sample, which belongs to the frosting sample treated at 23 °C and 90% relative humidity.

Interestingly, an optical microscope image was taken from the sample treated at 23 °C and 90% relative humidity and after freezing at −15 °C for 1 day, see Fig. 9. In the image, one can see the water condensed on the surface in frost form, among the fibers.

Furthermore, contact angle measurements as hydrophobicity tests were executed on the samples, once before the humidity and

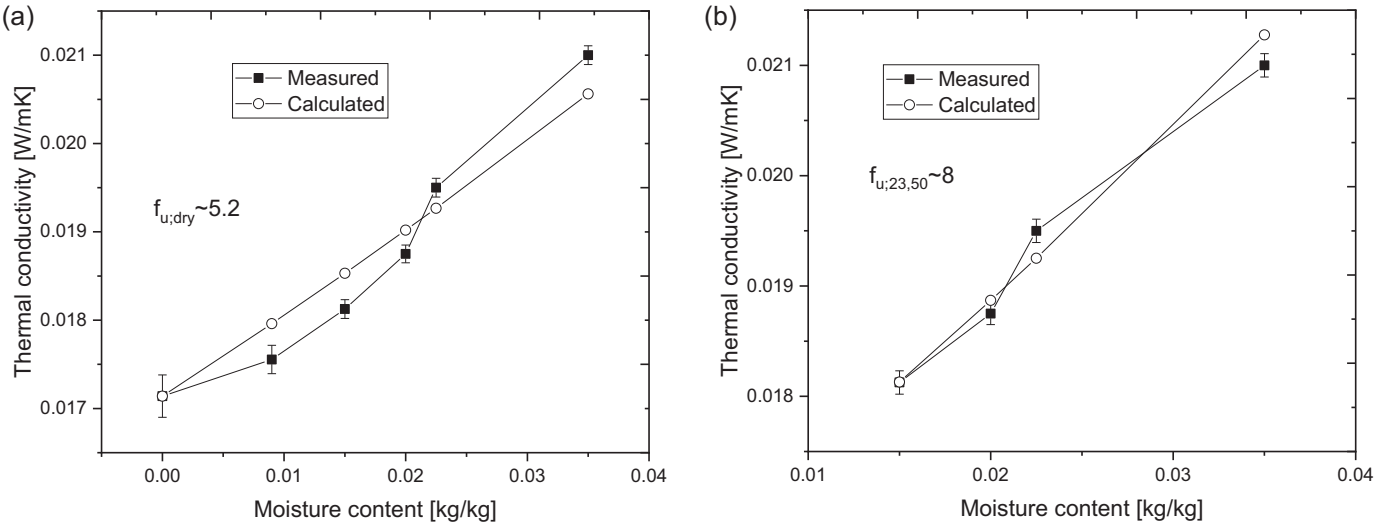

Fig. 5. (a) Thermal conductivity in the function of the moisture content (kg/kg) for the first case. (b) Thermal conductivity in the function of the moisture content (kg/kg) for the second case.

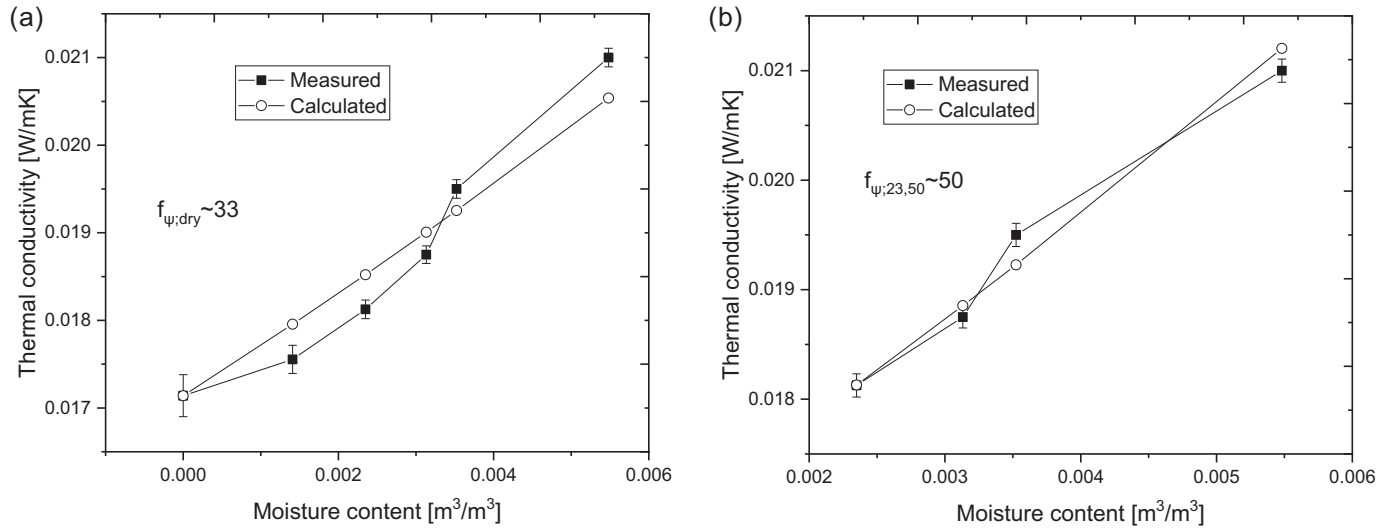

Fig. 6. (a) Thermal conductivity (lambda) in the function of the moisture content (m^3/m^3) for the first case. (b) Thermal conductivity (lambda) in the function of the moisture content (m^3/m^3) for the second case.

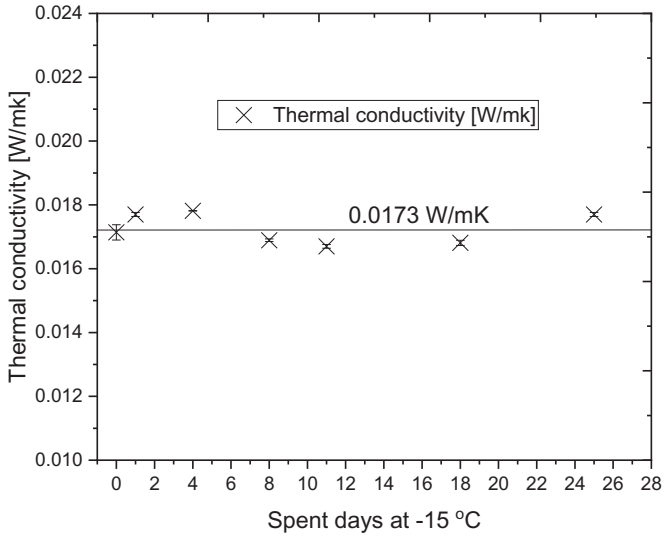

Fig. 7. Thermal conductivities (lambda) after treating the samples at −15 °C for weeks.

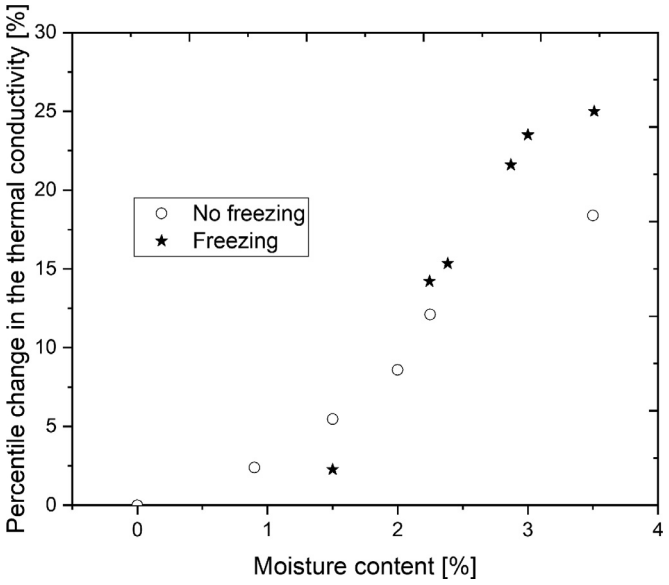

Fig. 8. Percentile change in the thermal conductivity (lambda) in the function of water+ice content.

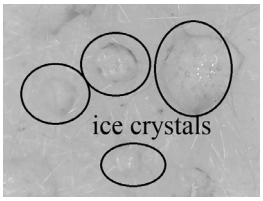

Fig. 9. Image of the sample treated at 23 °C and 90% relative humidity after freezing at −15 °C for 1 day.

frost treatment and after the curing (see Fig. 10a-c). The method is well presented in Ref. [33]. The results show an increasing contact angle after freezing the samples.

3.4. Extended theory for the thermal conductivity

In general the total thermal conductivity ($\lambda_{T,dry}$) of a dry insulation material can be given with the following:

$$\lambda_{T,dry}=\lambda_{c,g}+\lambda_r+\lambda_{c,s}+\lambda_{conv} \quad (9)$$

where the parts in the equation are the conductive part both of the gas filling ($\lambda_{c,g}$), and the solid material ($\lambda_{c,s}$), the radiation part (λ_r) and the convective part of the gas filling among the fibers λ_{conv} [5,9,31].

However, in humid environment the equation changes to:

$$\lambda_{T,wet}=\lambda_{c,g}+\lambda_r+\lambda_{c,s}+\lambda_{conv}+\lambda_{c,water}+\lambda_{diff} \quad (10)$$

where the above mentioned equation is completed with the conductive and the diffusive (λ_{diff}) part of the water ($\lambda_{c,water}$).

Furthermore, in cold environments, the equation should be modified with a conductive part ($\lambda_{c,ice}$) of the ice.

$$\lambda_{T,frost}=\lambda_{c,g}+\lambda_r+\lambda_{c,s}+\lambda_{conv}+\lambda_{c,ice} \quad (11)$$

In order to understand the process we have to emphasize that the thermal transport through a material in moist and cold environment should be faster, new parts should be taken into account in both cases. However, the convective and conductive parts of the

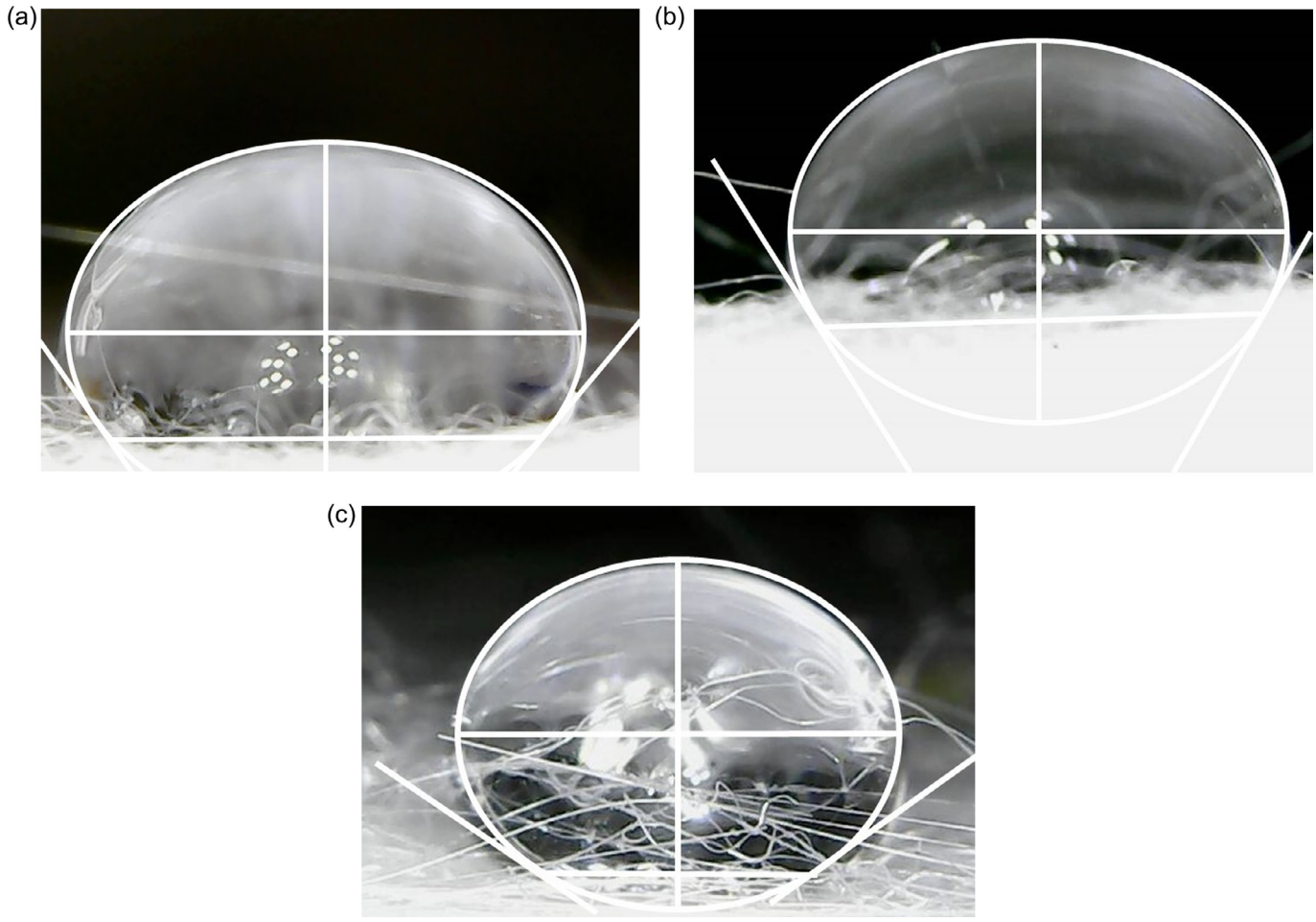

Fig. 10. (a) Wetting experiment on the as-received sample ($\theta = 125°$). (b) Wetting experiment on the rh treated (aged) sample ($\theta = 125°$). c. Wetting experiment on the sample treated at −15 °C for 28 days, ($\theta = 140°$).

gas became smaller, while the total thermal conductivity will be greater due to the presence of the water and in frost environment by the presence of ice inside the material, caused by the replacement.

In contrast to the papers of the topic presented in the scientific literature [5,9,10,13,15,33] where only the moisture-induced changes of the thermal conductivity were measured and presented, here the laboratory test results are once used for completing a standard for designers. Secondly, the humidity measurements are completed, investigating the thermal conductivity under the cold climate. Moreover, structural investigations were conducted on the samples, in order to find the reasons for the moisture up-taking effects. Furthermore, a theory based on the measurement results were given, too.

4. Conclusions

In the paper beside the investigation and presentation of hygric properties of aerogel samples, thermal conductivity measurements after freezing the dry and moist samples are presented. From the results the downer conclusion can be given:

- A new moisture-related coefficient (A_v) was specified from measurements. This value is similar in dimensions to the water absorption coefficient. Furthermore, the paper presented that this coefficient strongly depends on the partial pressure (relative humidity).
- From the measured thermal conductivities of moist samples, moisture conversion factors were defined for the tested spaceloft aerogel samples. The coefficients were characterized by moisture contents both in kg/kg and in m^3/m^3.
- A table was given as a completion of the ISO 10456 standard belonging to the tested fibrous aerogel sample. This supplement could be very useful both for designers, planners, and researchers.
- A new theory for the thermal conductivity of moist/frost insulations

Additionally, separately from the above-mentioned laboratory measurements, two new measurement rows were executed, in order to see the effect of the freezing (freeze-thaw cycles).

- Dried aerogel samples were treated in a freezing chamber at −15 °C for 25 days. By the interruption of the freezing process on given days, the thermal conductivities were measured. From the results, the paper states that thermal conductivity remains constant after the long-time freezing of the samples. The results were slightly varying near 0.0173 with ±3% W/mK.
- Another set of measurement row was executed by freezing the samples after wetting them at 23 °C for 35, 50, 65, 80 and 90% relative humidity till equilibrium. The moist samples were kept in the freezing chamber at −15 °C for 1 day and then their thermal conductivity was registered by the Holometrix Lambda 2000 equipment. During the test row the dry mass, the wet mass as well as the frost mass of the samples were measured by the balance. From the results, we could state that the freez-

ing has an effect in the thermal conductivity but only if the samples are moist. But the effect is significant only I the sample's moisture content is considerable.

Declaration of Competing Interest

The authors whose names are listed immediately below certify that they have NO affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

CRediT authorship contribution statement

Ákos Lakatos: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Resources, Supervision, Validation, Visualization, Writing - original draft, Writing - review & editing.

Acknowledgements

The research was financed by the Higher Education Institutional Excellence Programme (NKFIH-1150-6/2019) of the Ministry of Innovation and Technology in Hungary, within the framework of the Energy thematic program of the University of Debrecen.

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