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Effects of humidity on thermal performance of aerogel insulation blankets

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ABSTRACT

Actual thermal conductivity of insulation materials is subject to change over time under various environmental conditions. Particularly, insulations may degrade due to moisture absorption or condensation when they are exposed to humidity. This work presents a comprehensive investigation of aerogel blankets thermal conductivity (k-value) in humid conditions at transient and steady state regimes. Transient plane source (TPS) tests revealed that the k-value of aerogel blankets can increase by up to approximately 15% as the ambient relative humidity (RH) increases from 0% to 90% at 25 °C. In addition, a relatively long time is required, at constant T (temperature) and RH, for such enhancement. Therefore, mechanisms affecting the k-value of aerogel blankets as a function of RH and T are investigated. Also, theoretical approaches for predicting the moisture content and k-value over time are discussed, and parametric analyses are performed to identify the most affecting variables.

1. Introduction

Growing population has resulted in a significant increase in global energy consumption from buildings, which is ~ 20–40% in developed countries and has exceeded the industrial and transportation sectors. The rise in the time people spend inside buildings guarantees the upward trend in energy demand of both residential and commercial buildings in future [1]. As demand increases, the use of efficient thermal insulation is becoming essential, especially in harsh climates. Cost, environmental impact, flammability, transmission as well as thermal conductivity (k-value), are among important factors that should be considered in designing and selecting appropriate thermal insulation for any application.

Over the last few decades, it has been established that extensive failures in the performance of building components are often a result of thermal and moisture loads [2]. Temperature and humidity greatly affect the k-value of thermal insulations as well as indoor conditions [3]. In hot–humid climates, condensation can occur within the insulation material, raising its moisture content. This leads to higher thermal conductivity due to the enhanced heat transfer by conduction and, under certain conditions, by evaporation–condensation process in which moisture moves from warm to cold regions. The presence of moisture in insulation may also contribute to corrosion and degradation under the insulation layer. Additionally, moisture buildup can result in the growth of fungus and mold, which can affect the structural reliability of building components and occupants' health [4–6].

There are several studies that investigated the mechanism of moisture diffusion into porous materials as well as the effect of this phenomenon on variation of the k-value of conventional insulation materials. In the field of moisture diffusion analysis, Alvarez [7] experimentally studied different moisture diffusion models. He also developed an experimental apparatus to measure moisture transfer properties in porous materials under non-isothermal conditions. García et al. [8,9] performed a set of experiments to determine the diffusion coefficient of non-impregnated transformer insulating paper and oil-impregnated transformer insulating paper as a function of temperature, moisture concentration, insulation thickness and ageing degree of the insulation paper. Stephenson [10] used a set of published results on glass fiber insulation to estimate its thermal diffusion coefficient. His hypothesis was based on that moisture diffusion is related to the gradients of temperature and concentration at the same time. He concluded that the thermal vapor diffusion coefficient is approximately five times the coefficient for the diffusion due to the gradient of the vapor density.

Also, several studies have been performed on thermal performance of insulations in humid conditions. Thermal conductivities of brick [11,12,13], lime-based renders [4,5], and stone wool [14] were reported to grow quite a few times when the measured values were compared in two different states: dry and water saturated condition. The effect of moisture content on k-value of fibrous insulations was investigated in Ref. [15] and a relationship was presented to find the thermal conductivity at various moisture content at 24 °C and 34 °C. They showed that higher temperatures and higher moisture content was accompanied by higher thermal conductivity in fibrous insulations,

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Nomenclature

A	Area (m^2)
D	Diffusion coefficient ($m^2\,s^{-1}$)
x	Volume fraction
k	Thermal conductivity ($W\,m^{-1}\,K^{-1}$)
K_R	Mean extinction coefficient
l	Length (m)
t	Thickness (m)
$\dot{q}$	Heat flux ($W\,m^{-2}$)
r	Radius (m)
T	Temperature (K)
c	Concentration ($kg\,m^{-3}$)
V	Volume (m^3)
P	Pressure (Pa)
Z	Moisture supplement for the thermal conductivity

Greek symbols

ε	Porosity
σ	Stefan-Boltzmann constant
ω	Moisture content
φ	Volume fraction
Λ	Mean free path

Subscripts

b	Blanket
cond.	Conduction
eff	Effective
f	Fluid
g	Gas
fs	Fluid solid region
m	Medium around the fiber
s	Solid
tot	Total
rad.	Radiation
w	Water
v	Vapor

which was more pronounced in lower density materials. Jerman and Cerny [16] showed that the thermal conductivity of all mineral wools increased significantly with increasing moisture content; which was from the range of 0.10–0.14 $W\,m^{-1}\,K^{-1}$ to 0.7–0.9 $W\,m^{-1}\,K^{-1}$ at saturation. Ochs et al. [17] modified the analytical model of Krischer and Kast [18] for the effective thermal conductivity of porous materials having moisture content by adding the concept of closed pore to the humidity model. They verified the model for expanded glass granules and expanded clay using experimental data of guarded heating plate device. Fan and Wen [19,20] studied the initial water content and thickness of the fibrous insulation together with the environmental temperature as the three most important factors influencing the heat flux. They found that initial water content and temperature played a more important role than thermal conductivity of fibers and porosity. Björk and Enochsson [21] studied the moisture dependent heat transfer for three different thermal insulation materials: glass wool, melamine foam, and corrugated sheets of cellulose plastic. The materials were quite different with respect to condensate formation and maximum moisture accumulation at similar environmental conditions. They also showed that moisture content affected the heat transfer rate considerably.

Based on the above, it can be concluded that: i) moisture transport in building materials is directly responsible for structural damage; and ii) neglecting the moisture dependence of thermal conductivity of insulations, specifically aerogel based composites, in energy-related evaluations can lead to significant errors in heat loss calculations.

Aerogel blankets consist of polymeric fibers coated by aerogel particles making a highly porous material [22]. Their thermal conductivity can be lower than air at the same pressure and their exceptional insulation characteristics are due to the small size (~200 nm) of large number of pores. Because of the outstanding insulating properties of aerogel based composites, they drew an immense interest in recent years for many applications. Table 1 summarises the studies that have been performed on aerogel based materials in wet conditions:

As Table 1 indicates, there is a lack in the literature for systematic theoretical and experimental investigation of k-value of aerogel based materials at humidity. Therefore, there is a great need for developing analytical models that can accurately predict their thermal conductivity at various climatic conditions. The goal of the present paper is to identify and shed light on the effect of moisture diffusion on thermal performance of aerogel blankets by presenting a combined experimental and theoretical study of heat and moisture transfer. This study expands upon our previous work on the effect of temperature variation on thermal conductivity of aerogel blankets [29].

2. Experimental study

2.1. Materials

In this study, Cryogel®Z (CZ) supplied by Aspen Aerogel Inc. (Northborough, USA), and ThermalWrap™ (TW) supplied by Cabot Corporation, (Boston, USA) were studied as the representatives of aerogel blankets. The specifications for these highly porous, super insulation materials are listed in Table 2.

Table 1
Summary of available studies on aerogel and aerogel based composites at humid condition.

Author (s)	Notes
Lakatos [23,24]	• Experimental study of aerogel blankets thermal-physical properties in dry condition and after wetting • Building Energy Simulations to show the effect of moisture on heat energy demand and primary energy demand
Galliano et al. [25]	• Experimental study of transient hygrothermal properties of aerogel based and perlite composites for internal retrofit of a wall • Software simulations to evaluate transient hygrothermal properties by solving coupled heat and moisture transfer
Stahl et al. [26]	• Highly insulating material using aerogel granules was developed • Experimental measurements of thermal conductivity and water vapor transmission resistance of the material
Ihara et al. [27]	• Experimental measurements of water uptake of aerogel granules • Found that the liquid water enters the nano-pores of the aerogel granulate and damages the structure and requires a long time to dry
Wakili et al. [28]	• In-situ measurement of temperature, humidity, and heat flux on aerogel-based plasters • Not able to reach a quasi-steady state condition in about a year • Combined transient heat and moisture transfer suggested as future work

Table 2
Specifications of aerogel blanket samples used in this study.

Sample	Provider	Thickness[a]	Density[b]	Porosity[a] [29]	Mean extinction coefficient[a] [29]	Fiber composition	Powder material
Cryogel®Z (CZ)	Aspen Aerogel Inc.	5 mm	130 kg m^{-3}	91%	4014 m^{-1}	Polyester and fiber glass	Silica (SiO_2)
ThermalWrap™ (TW)	Cabot Corp.	5 mm	70 kg m^{-3}	79%	3165 m^{-1}	Polyester and polyethylene	Silica (SiO_2)

[a] Measured value.
[b] At room temperature.

2.2. Moisture content measurements

Moisture content prediction is a laborious task mainly due to the slow diffusion of moisture through porous materials, which makes the experimental study particularly long. In this study, water uptake of the aerogel blanket samples was measured following the ISO 12571:2013 Standard (Hygrothermal performance of building materials and products – Determination of hygroscopic sorption properties, Part B- climatic chamber method) [30]. Samples were placed in an environmental chamber, ESPEC Platinous series EPX-4H, capable of recreating wide range of temperature (10–85 °C) and relative humidity (0–98%) conditions. They were exposed to 0%, 40% and 90% RH at temperatures of 25 °C and 45 °C for 24 h wetting process. Weight of the samples was measured after each wetting period, using Ohaus Adventurer™ Balance having 0.0001 g standard deviation. Prior to moisture sorption tests, the samples were dried, for 24 h (According to our measurements the equilibrium was reached after 24 h and the samples were completely dried), at 70 °C under normal atmospheric pressure, and weighed to calculate the weight change after each wetting time. 70 °C is safe, as the maximum possible temperature that the samples can be used is reported 125 °C by the suppliers [31,32], and does not affect their physical and chemical structure.

2.3. Thermal conductivity measurements

Thermal conductivity measurements were performed as per ISO22007-2 [33], using a transient plane source (TPS) thermal constants analyzer (TPS 2500S, ThermTest Inc., Fredericton, Canada). The temperature controlled chamber was modified to create an input and exit port for the flow of air with controlled humidity and a humidity sensor was added to the chamber. The flow of humid air was provided by a Cellkraft F-series humidifier. The humidifier operates through water transfer across a perfluorinated sulphonic acid membrane and is suitable for accurate humidity control without droplets. It can measure the gas temperature with ± 0.2 °C accuracy in range of 0–50 °C and ± 1.7% for RH between 0% and 90%, i.e., the range used in this study. The temperature of the flowing humid air was matched to the temperature in the chamber. The flow rate was 6 nlpm (nominal litres per minute) with the RH under feedback control using the sensors within the chamber and the humidifier.

TPS device has several "hot disk" two-sided sensor types and software modules to conducts measurements on bulk materials (isotropic and anisotropic), thin films, powders and liquids. In this work, a sensor (TPS Hot Disk 7577) with a 2.001 mm radius nickel double spiral insulated in a thin layer of Kapton was used for simultaneous transient heating of the sample and precise temperature measurement. For bulk measurements, the sensor was placed between a pair of identical samples and compressed using a standard weight to minimize the thermal contact resistance. The sample-sensor assembly is shown in Fig. 1. Each test was repeated three times to ensure the repeatability of the results. Low standard deviation of the measured data about $2*10^{-4}$ W/m/K shows the reliability of the collected data. More details of the methodology used in the thermal conductivity measurements can be found in Ref. [34].

3. Model development

3.1. Aerogel blanket moisture content

When an aerogel blanket is placed in a humid environment, it takes hours for moisture to diffuse from the surface of the material to its depth and establish no concentration gradient inside the pores. The reason is that the material shows "resistance" against diffusion of humidity into the pores as well as providing a "capacity" to store moisture inside the pores. This phenomenon can be described using a well-established resistance-capacitance (RC) model that employs a representative electric circuit to simulate the mass diffusion in the aerogel blankets [35].

Modeling a mass transfer in a porous material using an RC model requires finding its equivalent electric circuit. Once the equivalent resistance and capacitance are defined and the circuit is set up, based on the analogous electrical network, the heat and mass transfer phenomena can be modeled using the solution to the electric circuit [36–39]. This method is widely used in numerous industrial applications such fuel cell systems [40–43]. The proposed zero-dimensional RC circuit (lumped system) for aerogel blanket porous medium is shown in Fig. 2 and the equivalent parameters are shown in Table 3.

In Fig. 2, once the switch is closed at $t = 0$ s, the moisture diffuses and charges the insulation (capacitor) till it is fully charged (the current become zero). The resistance against the diffusion of moisture (R_{diff}) is defined following Fick's law and is shown in Eq. (1):

$$R_{diff} = \frac{t_s}{D \cdot A_s} \tag{1}$$

where D is the diffusion coefficient of moisture; t_s and A_s are thickness and the cross sectional area of the sample, respectively.

Also, C shows the mass storage capacitance of the system that can be

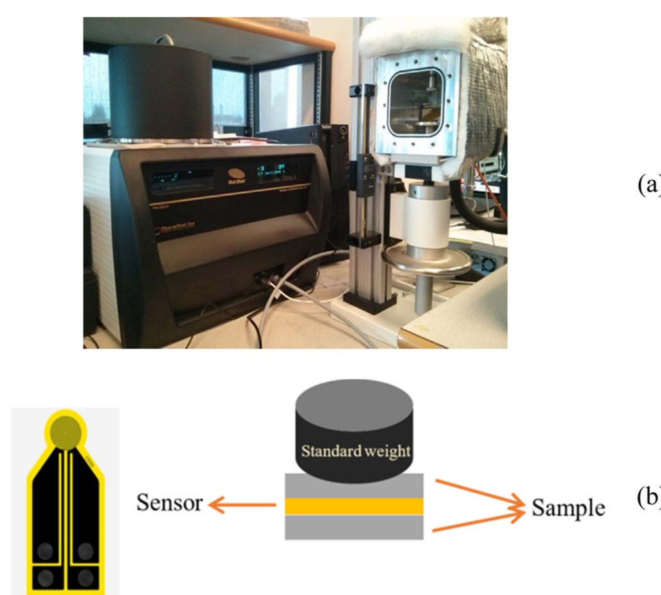

Fig. 1. Device (a) and simplified schematic of TPS (Transient Plane Source thermal conductivity measurement) (b).

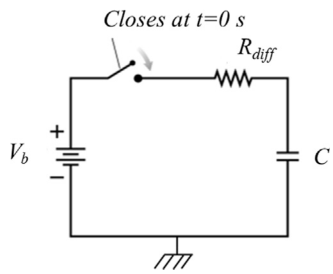

Fig. 2. Zero-dimensional (lumped) RC model of aerogel blanket insulation material in humid conditions.

Table 3
Table of equivalent parameters in electrical and mass transfer systems.

Electrical system	Mass transfer system
Current (*I*) [=] ampere = coulomb/s	Water flow rate ($\dot{m}_w$) [=] kg/s
Potential difference (*V*) [=] volts	Water vapor concentration (C_w) [=] kg/m^3
Electron charge (*Q*) [=] coulombs	Moisture content (m_w) [=] kg
Electric capacitance (C) [=] Farad = coulomb/volt	Mass storage capacitance [=] m^3
Electric resistance (R) [=] Ohm = volts s/coulomb	Diffusion resistance [=] s/ m^3

calculated using the maximum charge that a capacitor can hold (Q_{max}) and the voltage of the source (V_b) [44]. In this study, the moisture content of the material (m_w) and moisture concentration (c_w) in the porous medium are equivalent to the electron charge (*Q*) and potential difference (*V*) in the electrical system, respectively. Hence, having the maximum moisture content of the aerogel blanket samples, which has been measured as discussed in Section 2.2, the mass storage capacitance can be calculated using Eq. (2):

$$C = \frac{Q_{\max}}{V} = \frac{m_{w\_\max}}{c_w} \quad (2)$$

where m_{w_max} is the weight of the moisture in the sample at steady-state condition. c_w is also calculated assuming water vapor is an ideal gas:

$$c_w = \frac{M_w \cdot P_{sat}}{R \cdot T}(RH) \quad (3)$$

where M_w is the molecular weight of water; R is gas universal constant and T is temperature. P_{sat} is the saturation pressure of water vapor calculated from Eq. (4)

$$P_{sat} = 610.78\exp(\frac{17.27T + 4717.30}{T}) \quad (4)$$

Therefore, moisture content of the samples over time is calculated using Ohm's law and voltage law for a circuit of series capacitor and resistor, according to Eq. (5):

$$m_w = m_{w\_\max}[1 - e^{-t/\tau}] \quad (5)$$

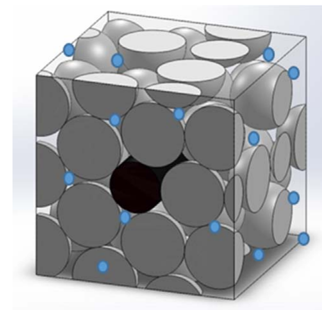

Fig. 4. Schematic of the moisture distribution inside the pores of the proposed unit cell; small blue circles depict water droplets. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

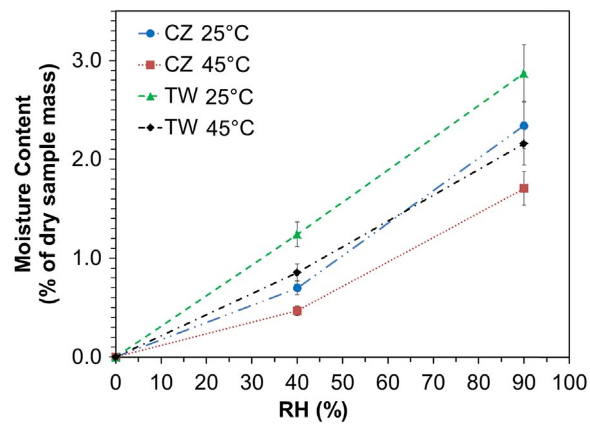

Fig. 5. Sorption isotherms at 25 °C and 45 °C for CZ and TW aerogel blanket samples.

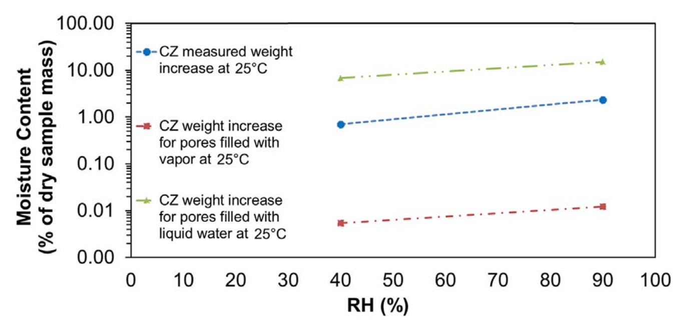

Fig. 6. CZ weight increase in three cases: blue line: actual measured data; red line: water vapor filled the pores; and green line: liquid water filled pores. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

where τ is the time constant of the system and is calculated as follows:

$$\tau = R_{diff} \cdot C \quad (6)$$

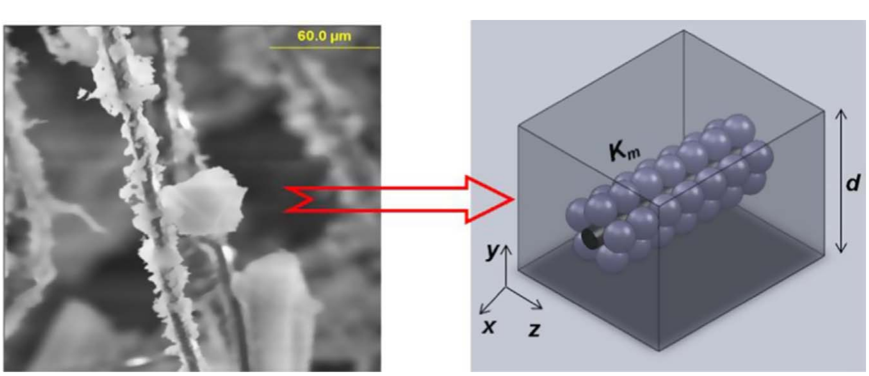

Fig. 3. Proposed unit cell for geometrical modeling of aerogel blanket thermal conductivity [29].

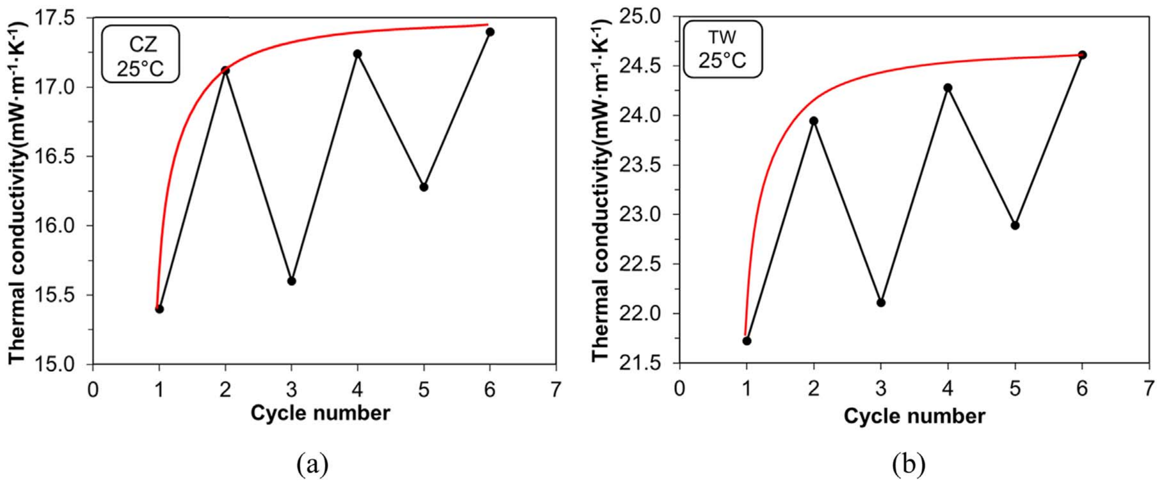

Fig. 7. Cyclic thermal conductivity measurements of CZ and TW between 0% and 80% RH at 25 °C.

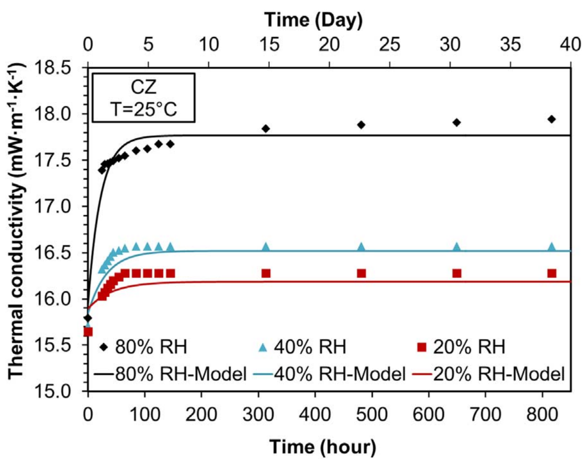

Fig. 8. Thermal conductivity of CZ over time at 25 °C and 20%, 40% and 80% RH.

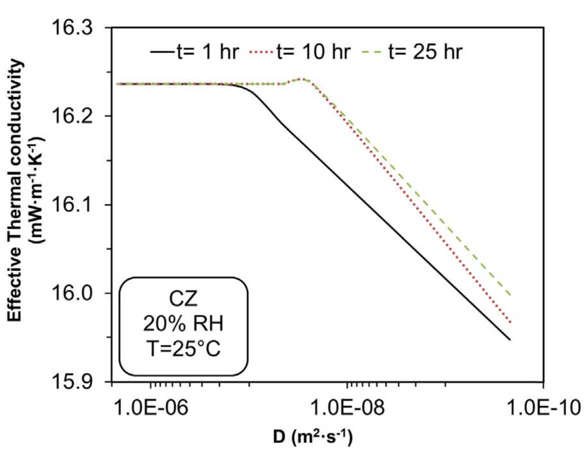

Fig. 9. Sensitivity analysis on CZ diffusion coefficient at 20% RH and 25 °C.

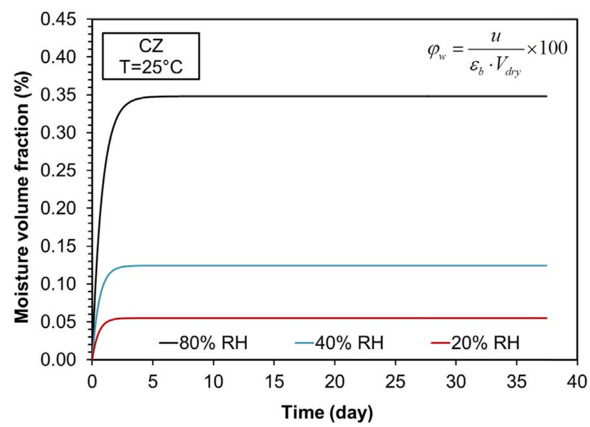

Fig. 10. Moisture volume fraction of CZ over time at 25 °C.

Table 4
Diffusion parameters of CZ at different RH.

	20% RH	40% RH	80% RH
D ($m^2\,s^{-1}$)	2.2×10^{-9}		
τ (h)	12.37	14.00	19.59

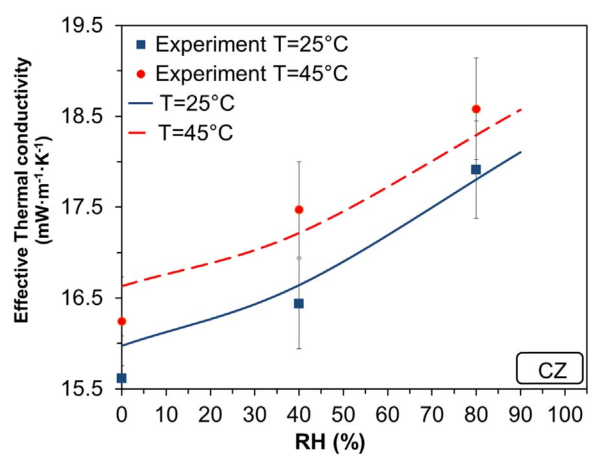

Fig. 11. Effective thermal conductivity as a function of RH for CZ at 25 °C and 45 °C.

Predicting the moisture content of aerogel blanket materials over time enables us to predict their k-value at any given time under any T and RH condition.

3.2. Aerogel blanket effective thermal conductivity

Using SEM images of the samples (Fig. 3), a basic cell is introduced to represent the structure of aerogel blankets. A unit cell is a small geometrical block that can describe main salient properties of the medium and is assumed to be repeated throughout the structure, see our previous paper for more information on the unit cell approach [29]. The proposed unit cell is composed of a packed bed of spherical aerogel particles with more than 90% porosity and a solid cylindrical fiber at its

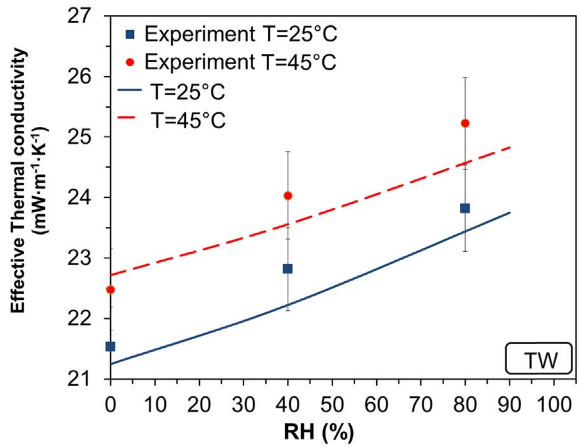

Fig. 12. Effective thermal conductivity as a function of RH for TW at 25 °C and 45 °C.

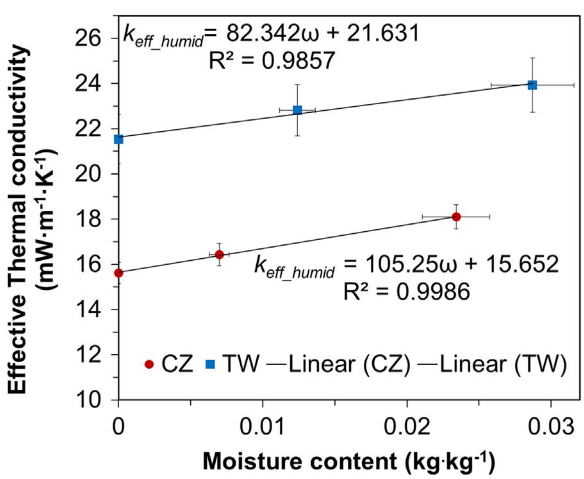

Fig. 13. The change in the thermal conductivity as a function of moisture content. At 25 °C.

center. Following our pervious paper [29], solid-gas conduction as well as radiation are modeled as two parallel paths of one dimensional heat transfer in aerogel blankets, according to Eq. (7):

$$\dot{q}_{tot} = k_{eff} A\frac{dT}{dz} = \dot{q}_{cond.} + \dot{q}_{rad.} \tag{7}$$

When a material is optically thick, such as a 1 cm thick insulation layer, radiation heat transfer can be modeled using Fourier conduction law, as is shown in Eq. (8), and it is called diffusion approximation method [45].

$$\dot{q}_{rad.} = k_{rad.} A\frac{dT}{dz} \tag{8}$$

where the corresponding conductivity coefficient, k_{rad}, is defined according to Eq. (9) [46]:

$$k_{rad} = \frac{16\sigma T^3}{3K_R} \tag{9}$$

In this equation $\sigma = 5.67 \times 10^{-8}$ W m^{-2} K^{-4} is Stefan-Boltzmann constant, and K_R is Rosseland mean extinction coefficient of the material, which is shown in Table 2 for both considered samples.

For calculating the contribution of solid and fluid conduction heat transfer, Fourier conduction law is used following Eq. (10):

$$\dot{q}_{cond.} = k_{cond.} A\frac{dT}{dz} \tag{10}$$

where $k_{cond.}$ is the conduction heat transfer coefficient. In Ref. [29], a compact relationship as a function of aerogel blanket salient geometrical parameters (ε_m, k_{fiber}, r_{fiber} etc.) was developed analytically to calculate $k_{cond.}$:

$$k_{cond.} = \frac{k_m[4\sqrt{2}(\frac{r_{fiber}}{d})^2(k_{fiber} - k_m) + 1.77(k_{fiber} + k_m)]}{-4\sqrt{2}(\frac{r_{fiber}}{d})^2(k_{fiber} - k_m) + 1.77(k_{fiber} + k_m)} \tag{11}$$

where k_{fiber} is the thermal conductivity of the fiber, r_{fiber} is the fiber radius and d is the length of the unit cell [29]. k_m is the thermal conductivity of the effective medium around the fiber that consists of aerogel particles and the stagnant fluid, which is air for dry condition (RH = 0%). In Ref. [29], this medium was modeled as a packed bed of spherical particles of aerogel, following Zehner-Schlunder modified model [47], as below:

$$k_m = (1 - \sqrt{(1 - \varepsilon_m)})k_f + \sqrt{(1 - \varepsilon_m)}(1 - r_s^2)k_{fs} + \sqrt{(1 - \varepsilon_m)}\, r_s^2 k_s \tag{12}$$

k_m includes the conduction heat transfer through the interstitial fluid filling the pores and the conduction through aerogel particles. k_{fs} is the equivalent thermal conductivity of the region of packed bed unit cell made up of fluid and solid phases, r_s is the radius of contact area between two spheres, and k_f and k_s are the fluid and solid (silica aerogel) thermal conductivities, respectively.

In a humid environment, pores would be partially filled with water vapor as well as water droplets, as shown schematically in Fig. 4.

The amount of water droplets, depicted in Fig. 4, is assumed to be distributed evenly throughout the medium of the unit cell. Considering that in humid conditions pores include humid air (known RH) as well as water droplets, the medium thermal conductivity of the unit cell, k_m, should be re-defined accordingly:

$$k_{m\_humid} = (1 - \sqrt{(1 - \varepsilon_{m\_humid})})k_{f\_humid} + \sqrt{(1 - \varepsilon_{m\_humid})}(1 - r_s^2)\, k_{fs\_humid} + \sqrt{(1 - \varepsilon_{m\_humid})}\, r_s^2 k_s \tag{13}$$

where k_{m_humid} is the medium thermal conductivity at humid conditions. k_{f_humid} is estimated from Maxwell-Euken model for calculating the thermal conductivity of the mixture of fluids; i.e. humid air as the gas phase (k_g), and water droplets (k_w) [48]:

$$k_{f\_humid} = k_w\frac{2k_w + k_g - 2(k_w - k_g)\varphi_g}{2k_w + k_g + (k_w - k_g)\varphi_g} \tag{14}$$

In Eq. (14), φ_g is the volume fraction of humid air inside the pores, calculated using Eq. (15):

$$\varphi_g = 1 - \varphi_w \tag{15}$$

where φ_w is the volume fractions of water droplets inside the pores, which can be calculated having water content of the samples over time, as is shown in Eq. (16) and Eq. (17). It should be noted that the aerogel materials are super hydrophobic and do not adsorb moisture, i.e. water and humid air fill up the pores.

$$\varphi_w(t) = \frac{u(t)}{\varepsilon_b \cdot V_{dry}} \tag{16}$$

$$u(t) = \frac{m_w(t)}{\rho_w} \tag{17}$$

where *u(t)* is the volume of the water droplets inside the sample over time, in m^3, and $m_w(t)$ is the moisture content of the sample, in kg. Moisture content modeling over time has been discussed in Section 3.1. ρ_w is the density of water, V_{dry} and ε_b are volume and porosity of the dry blanket, respectively. Porosity was measured using a Mercury Intrusion Porosimetry device (AutoPore IV, Micromeritics Instrument Corporation) and reported in Table 2 for both aerogel blanket samples.

Thermal conductivity of water is estimated using Eq. (18) [17]:

$$k_w = 0.557 + 0.0022(T + 273) - 1.051 \cdot 10^{-5}(T + 273)^2 + 1.081 \cdot 10^{-8}(T + 273)^3 \tag{18}$$

In aerogel blankets the pores are small ($d_p < 300$ nm) and bulk thermal conductivity of the gas needs to be modified to include Knudsen regime effect. In Knudsen regimes, the gas thermal conductivity varies as a function of pore diameter in which the gas is stored. Therefore, thermal conductivity of humid air should be modified as follows [49]:

$$k_g = \frac{k_{g_0}}{1 + 2\xi Kn} \tag{19}$$

The coefficient ξ is a parameter calculated from the gas accommodation coefficient, α_T, and the specific heat ratio of gas, γ.

$$\xi = \left(\frac{9\gamma - 5}{2\gamma + 1}\right)\left(\frac{2 - \alpha_T}{\alpha_T}\right) \tag{20}$$

For dry air α_T is 0.8 and γ is 1.4 at room temperature [50]. Kn is Knudsen number defined as $Kn = \Lambda_m / d_p$ in which d_p is the mean pore size of the aerogel blanket samples. Λ_m is the mean free path of gas molecules in free space, calculated as:

$$\Lambda_m = \Lambda_{m_0} \frac{P_0}{P} \frac{T}{T_0} \tag{21}$$

Λ_{m0} is in standard condition (~ 69 nm for air [51]), P_0 and T_0 are standard pressure and temperature (1 atm and 298 K).

k_{g0} is defined as thermal conductivity of the ideal mixture of water vapor and air at standard condition. It can be calculated knowing the volume fraction of water vapor and air as shown in Eq. (22):

$$k_{g_0} = x_v k_v + (1 - x_v) k_{air} \tag{22}$$

where x_v is the volume fraction of water vapor calculated having RH and T as follows:

$$x_v = RH \frac{P_{sat}}{P_{amb}} \tag{23}$$

where P_{amb} shows the ambient pressure (1 atm). Since volume fraction of vapor is an insignificant value in the considered T and RH, in Eq. (22), the first term is negligible ($x_v k_v \ll (1-x_v) k_{air}$), and k_{g0} can be estimated just by knowing the dry air thermal conductivity ($k_{g0} \approx k_{air}$). Thermal conductivity of dry air is calculated from Eq. (24) [17]:

$$k_{air} = 0.00243 + 7.8421 \times 10^{-5}(T + 273.15) - 2.0755 \times 10^{-8}(T + 273.15)^2 \tag{24}$$

The remaining parameter in Eq. (13), k_{fs_humid}, is calculated having all the defined parameters:

$$k_{fs\_humid} = \frac{2k_{f\_humid}}{1 - \frac{k_{f\_humid}}{k_s}} \left(\frac{1}{1 - \frac{k_{f\_humid}}{k_s}} \ln\left(\frac{1}{\frac{k_{f\_humid}}{k_s}}\right) - 1 \right) \tag{25}$$

Finally, presented in Eq. (26) is the final relationship for the effective thermal conductivity of the aerogel blanket at humid condition obtained by superposition of the modified conduction and radiation thermal conductivities following [52]:

$$k_{eff\_humid} = k_{cond\_humid} + k_{rad.} \tag{26}$$

3.3. Moisture supplement for the thermal conductivity (Z constant)

Effect of the diffused moisture on thermal conductivity is typically reported by the percentage of the difference in wetness levels. According to Refs. [23] and [53] a simple approximate can be used to find the aerogel blanket moisture supplement for the thermal conductivity (Z constant) following Eq. (27):

$$k_{eff\_humid} = k_{eff\_dry}(1 + (\omega Z/100)) \tag{27}$$

where k_{eff_humid} and k_{eff_dry} are the thermal conductivity of the humidified sample and the dried sample, respectively. ω is the non-dimensional moisture content (kg/kg) calculated using Eq. (28) following the mentioned method in Section 2.2:

$$\omega(\%) = \frac{m_{humid} - m_{dry}}{m_{dry}} \times 100 \tag{28}$$

Z is the material constant, demonstrates the moisture supplement for the thermal conductivity.

4. Results and discussion

4.1. Sorption isotherm measurements

Sorption isotherms (the moisture taken up from the air as a function of RH), is one of the important characteristics of materials. Due to the complexity of sorption processes, isotherms cannot be calculated theoretically and should be measured experimentally for each material [23].

Fig. 5 shows the sorption isotherms for the samples of aerogel blanket at two different temperatures to see the effect of temperature on moisture content as well. The error bars show the standard deviation of the measurements. The plots demonstrate that increasing humidity and decreasing temperature increase the moisture content. Furthermore, the maximum amount of moisture uptake is 2.87% of dry mass for TW and 2.34% of dry mass for CZ measured at 25 °C. Fig. 6 clearly shows that the observed weight increase in the samples after wetting is due to water droplet formation inside the pores, i.e., if all the pores were filled with water vapor (at given RH and T), the weight increase of the samples would be order of magnitudes less than the measured values. Therefore, weight of the water vapor has been neglected in the modeling section, compared to the liquid water, and the defined moisture content (m_w) just shows the weight of the water droplets.

4.2. Thermal conductivity analysis at transient regime

For each aerogel blanket type, two 5 mm thick pairs of 5 cm × 5 cm square samples were prepared to be tested at different levels of RH and temperature using our TPS device. Cyclic thermal conductivity measurements of aerogel blankets were performed between 0% and 80% RH, with power of 10 mW and measurement time of 40 s in short intervals. In Fig. 7, each data point was measured after 5 h rest time, after changing the humidity condition. The measured data revealed that thermal conductivity was increased over time, at cycles with same RH. This can be interpreted as a result of moisture building up inside the pores. It also shows that it should take more than 5 h for the moisture to leave the pores. Besides, it is observed that after approximately six cycles, the effective thermal conductivity reaches its maximum, which means the material was holding all the humidity that it could.

To find the diffusion coefficient (D) defined in Eq. (1), a series of long-term experiments on CZ were performed using TPS. The dry sample was placed inside TPS at 25 °C, under fixed conditions of 20%, 40% and 80% RH for more than a month and the thermal conductivity was measured at different time intervals from 5 h to weeks to ensure that steady-state was reached. Before each set of measurements, the dry sample was tested for 24 h at 0% RH, in different time intervals to ensure that its thermal conductivity remains constant over time.

Genetic algorithm optimization method (with the parameters of: population size of 50, generations and selection rate of 100%, migration rate of 10% and mutation rate of 90%) [9] was applied on the data set of 80% RH, to obtain the diffusion coefficient (D) of CZ. The objective function is shown in Eq. (29):

$$min\ error = sum(k_{eff\_humid\_model}(t) - k_{eff\_humid\_data}(t))^2 \tag{29}$$

The fitted value of D was used for modeling the moisture content of CZ at any other RH condition following Eq. (5). Since the model accurately predicts the data set of 20% and 40% RH, as shown in Fig. 8, the fitted value of *D* is reliable. A sensitivity analysis on the typical values of *D* is presented in Fig. 9 for three times after changing the RH to 20%, i.e., 1 h, 10 h and 25 h. It shows that changing *D* in the range of 10^{-10}–10^{-6} m^2/s changes the effective thermal conductivity less than 2%. It also demonstrates that at the beginning of the diffusion process (t = 1 h), the diffusion coefficient has a stronger effect on the effective k-value compared to steady st ate condition.

Fig. 8 shows that it took about 20 h for thermal conductivity of CZ at 80% RH to reach steady state condition, which is due to the diffusion resistance and storage capacitance of the sample. Water volume fraction increase is also shown over time in Fig. 10, which indicates that in a humid environment, moisture gradually replaces air in the pores until no concentration gradient throughout the sample exists.

Values of diffusion coefficient (*D)* and time constant (τ) are shown in Table 4. As is shown in Table 4, it takes more time for CZ to reach to steady state condition at higher RH, because of the higher vapor partial pressure gradient between the dry aerogel and the ambient at higher RH.

4.3. Thermal conductivity analysis at steady-state regime

The thermal conductivity of each pair of samples was measured in TPS with a power of 10 mW, measurement time of 40 s and rest interval of 24 h between measurements to ensure steady state condition. Fig. 11 and Fig. 12 present the effective thermal conductivity of aerogel blanket samples as a function of RH at two temperatures of 25 °C and 45 °C.

Results show that increasing the RH from 0% to 90% increases the k-value ~ 14% for CZ and ~ 11% for TW after reaching steady-state. This thermal conductivity increase is a result of liquid droplet accumulation inside the pores at higher RH that replaces the dry air and results in higher heat transfer rate inside the material. Also, according to Fig. 11 and Fig. 12, the modeling results at 25 °C and 45 °C (the Solid and dash line) become closer at higher RH. It is due to having more moisture content at the lower temperature (See Fig. 5), which leads to a sharper thermal conductivity increase at 25 °C.

According to Eq. (27), Z constant of CZ and TW at 25 °C can be calculated from Fig. 13. The slope of the curve shows $k_{eff\_dry} \times Z$ and the intercept represent k_{eff_dry}. Therefore, moisture supplement of the thermal conductivity of CZ and TW are 6.72 and 3.81, respectively.

5. Conclusion

In this paper, a comprehensive experimental and theoretical study on thermal performance of two types of aerogel blankets were performed considering the effect of moisture content and temperature at transient and steady state conditions. The findings can be summarized as:

- Moisture build up in two aerogel blanket samples were measured as a function of RH and temperature. The results showed that moisture content increased at higher RH and lower temperature.
- Experimental results of TPS-humidifier at steady state condition revealed that the effective thermal conductivity of the investigated samples increased by increasing temperature and RH. This trend can be explained by considering the higher thermal conductivity of the inbuilt moisture compared to dry air as the filling fluid inside the pores.
- Thermal conductivity cyclic tests showed that it took approximately six cycles till the effective thermal conductivity reaches its maximum, which means the material was holding all the humidity that it could
- A new moisture diffusion model was introduced using the concept of RC circuit, based on the analogy between electrical and mass transfer phenomena.
- The results of the long-term experiments on thermal conductivity of CZ at 80% RH and 25 °C were used to estimate the value of mass diffusion resistance coefficient as an input in the RC model to predict the moisture content of the sample over time.
- The values of time constants at different RH showed that at higher RH more time was required to reach steady state condition since the material has higher capacitance for moisture storage.
- Moisture supplement for the thermal conductivity of CZ and TW was calculated at 25 °C which are Z = 6.72 and 3.81, respectively.

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