Effect of moisture build up on thermal conductivity of aerogel 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 up to ~14% 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 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. Keywords: Aerogel blankets; composites; RC model; Transient plane source; humidifier; Relative humidity

1. Introduction

Growing population has resulted in a significant increase in global energy consumption from buildings, which is ~20% to 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.

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]. 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.

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. Also, several studies have been performed on thermal performance of insulations in humid conditions. Thermal conductivities of brick [11], lime-based renders[4], 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℃ and 34℃. They showed that higher temperatures and higher moisture content was accompanied by higher thermal conductivity in fibrous insulations, 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 $W\cdot m^{-1}\cdot K^{-1}$ to 0.7–0.9 $W\cdot m^{-1}\cdot K^{-1}$ 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.

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]. 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:

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

Author(s)	**Notes**
Lakatos [23]	• Experimental study of aerogel blankets thermal-physical properties after wetting • Building Energy Simulations to show the effect of moisture on heat energy demand and primary energy demand
Galliano et al. [24]	• 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.[25]	• Highly insulating material using aerogel granules was developed • Experimental measurements of thermal conductivity and water vapor transmission resistance of the material
Ihara et al.[26]	• 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. [27]	• 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

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 [28].

2. Experimental Study

2.1 Materials

The specifications for the representatives of aerogel blankets studied in this paper are listed in Table 2.

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

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

[a]At room temperature
*Measured value

2.2 Moisture content measurements

In this study, moisture buildup 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) [29]. Samples were placed in an environmental chamber, ESPEC Platinous series EPX-4H, capable of recreating wide range of temperature (10°C-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 hours wetting process. Weight of the samples was measured after each wetting period, using Ohaus Adventurer™ Balance having 0.0001g standard deviation. Prior to moisture sorption tests, the samples were dried, for 24 hours 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 insulation materials can be used is reported 125°C by the supplier[30], [31], and does not affect their physical and chemical structure.

2.3 Thermal conductivity measurements

Thermal conductivity measurements were performed as per ISO22007-2[32], 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 ±0.2ºC accuracy in range of 0 to 50ºC and ±1.7% for RH between 0 to 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 Figure 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} $W \cdot m^{-1} \cdot °K^{-1}$) shows the reliability of the collected data.

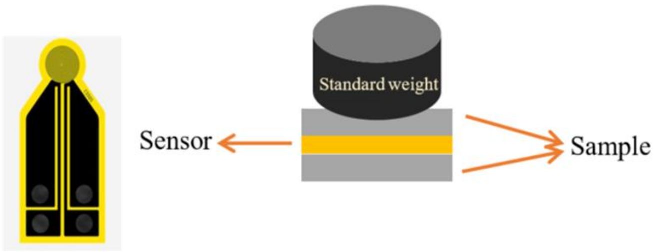

Figure 1. Simplified schematic of TPS (Transient Plane Source) device

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 [34].

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 [35]–[38]. This method is widely used in numerous industrial applications such fuel cell systems[39]–[42]. The proposed zero-dimensional RC circuit (lumped system) for aerogel blanket porous medium is shown in Figure 2.

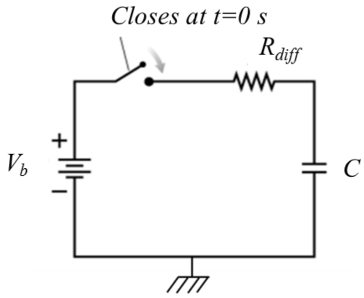

Figure 2. Zero-dimensional (lumped) RC model of aerogel blanket insulation material in humid conditions.

In Figure 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):

$$R_{diff} = \frac{t_s}{D \cdot A_s} \quad (1)$$

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 calculated using the maximum charge that a capacitor can hold (Q_{max}) and the voltage of the source (V_b) [43]. 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):

$$C = \frac{Q_{\max}}{V} = \frac{m_{w\_\max}}{c_w} \tag{2}$$

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:

$$c_w = \frac{M_w \cdot P_{sat}}{R \cdot T} RH \tag{3}$$

where M_w is the molecular weight of water; R is gas universal constant, T is temperature and P_{sat} is the saturation pressure of water.

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. (4):

$$m_w = m_{w\_\max}[1 - e^{-t/\tau}] \tag{4}$$

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

$$\tau = R_{diff} \cdot C \tag{5}$$

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 (Figure 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 [28]. The proposed unit cell is composed of a packed bed of spherical aerogel particles with more than 90% porosity and a solid cylindrical fibre at its centre. Following our pervious paper [28], solid-gas conduction as well as radiation are modelled as two parallel paths of heat transfer in aerogel blankets.

$$\dot{q}_{tot} = k_{eff} A \frac{dT}{dz} = \dot{q}_{cond.} + \dot{q}_{rad.} \tag{6}$$

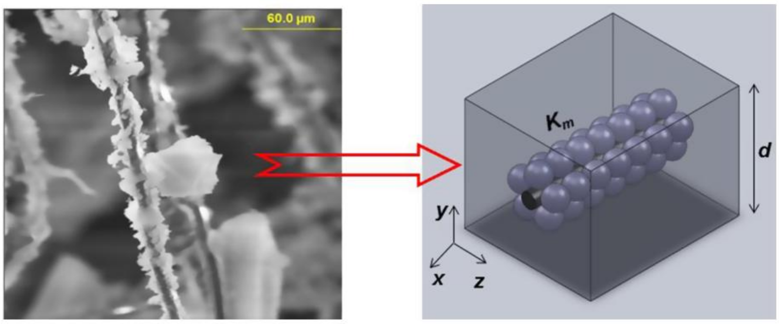

Figure 3. Proposed unit cell for geometrical modelling of aerogel blanket thermal conductivity [28]

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. (7), and it is called diffusion approximation method [44].

$$\dot{q}_{rad.} = k_{rad.} A \frac{dT}{dz} = \frac{16\sigma n^2 T^3}{3K_R} A \frac{dT}{dz} \tag{7}$$

In this equation, σ=5.67×10^{-8} W·m^{-2}·K^{-4} is Stefan-Boltzmann constant, n is the index of refraction, 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.(8):

$$\dot{q}_{\text{cond.}} = k_{\text{cond.}} A \frac{dT}{dz} \quad (8)$$

where $k_{cond.}$ is the conduction heat transfer coefficient. In Ref. [28], a compact relationship as a function of aerogel blanket salient geometrical parameters (ε_m, k_f, r_f *etc.*) was developed analytically to calculate $k_{cond.}$:

$$k_{cond.} = \frac{k_m[4\sqrt{2}(\frac{r_f}{d})^2(k_{fiber} - k_m) + 1.77(k_{fiber} + k_m)]}{-4\sqrt{2}(\frac{r_f}{d})^2(k_{fiber} - k_m) + 1.77(k_{fiber} + k_m)} \quad (9)$$

where k_{fiber} is the thermal conductivity of the fiber, r_f is the fiber radius and d is the length of the unit cell. 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. In Ref. [28], this medium was modeled as a packed bed of spherical particles of aerogel, following Zehner-Schlunder modified model [45], as below:

$$k_m = (1 - \sqrt{(1-\varepsilon_m)})k_f + \sqrt{(1-\varepsilon_m)}(1 - r_s^{\,2})k_{fs} + \sqrt{(1-\varepsilon_m)}r_s^{\,2}k_s \quad (10)$$

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' is the radius of packed bed unit cell, 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 Figure 4.

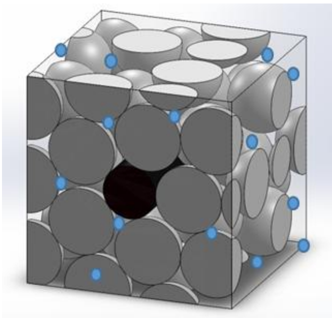

Figure 4. Schematic of the moisture distribution inside the pores of the proposed unit cell; small blue circles depict water droplets

The amount of water droplets, depicted in Figure 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:

$$k_{m\_\text{wet}} = (1 - \sqrt{(1-\varepsilon_m)})k_{f\_\text{wet}} + \sqrt{(1-\varepsilon_m)}(1 - r_s^{\,2})k_{fs\_\text{wet}} + \sqrt{(1-\varepsilon_m)}r_s^{\,2}k_s \quad (11)$$

where k_{m_wet} is the medium thermal conductivity at humid conditions. k_{f_wet} 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) [46]:

$$k_{f\_\text{wet}} = k_{\text{w}} \frac{2k_{\text{w}} + k_g - 2(k_{\text{w}} - k_g)\varphi_g}{2k_{\text{w}} + k_g + (k_{\text{w}} - k_g)\varphi_g} \quad (12)$$

In Eq.(12), φ_g is the volume fraction of humid air inside the pores, calculated using Eq.(13):

$$\varphi_g = 1 - \varphi_w \quad (13)$$

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.(14) and Eq.**Error! Reference source not found.**. 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.

$$\varphi_w(t) = \frac{m_w(t)}{\rho_w \cdot \varepsilon_b \cdot V_{dry}} \quad (14)$$

where $m_w(t)$ 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.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. Finally, the remaining parameter in Eq.(11), k_{fs_wet}, is calculated having all the defined parameters.

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].
Following the mentioned method in section 2.2, non-dimensional moisture content (ω) was calculated using Eq.(15):

$$\omega(\%) = \frac{m_{wet} - m_{dry}}{m_{dry}} \times 100 \quad (15)$$

Figure 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 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.

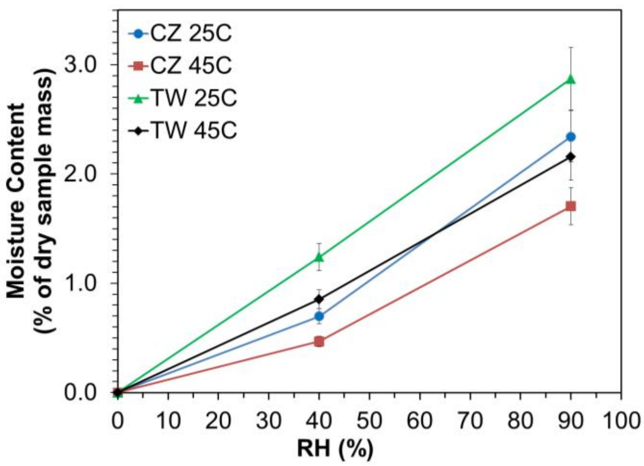

Figure 5. Sorption isotherms at 25°C and 45°C for CZ and TW aerogel blanket samples

4.2 Transient heat transfer

For each aerogel blanket type, two 5 mm thick pairs of 5cm×5cm 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 10mW and measurement time of 40s in short intervals. 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. Besides, it was 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 hours to weeks. Before each set of measurements, the dry sample was tested for 24 hours at 0% RH, in different time intervals to ensure that its thermal conductivity remains constant over time.
Applying a genetic algorithm optimization method on the data set of 80% RH, the best fit for the diffusion coefficient of CZ was found and used for modelling the moisture content of CZ at any other RH condition following Eq.(4). Since the model accurately predicts the data set of 20% and 40% RH, as shown in Figure 6, the fitted value of *D* is reliable.

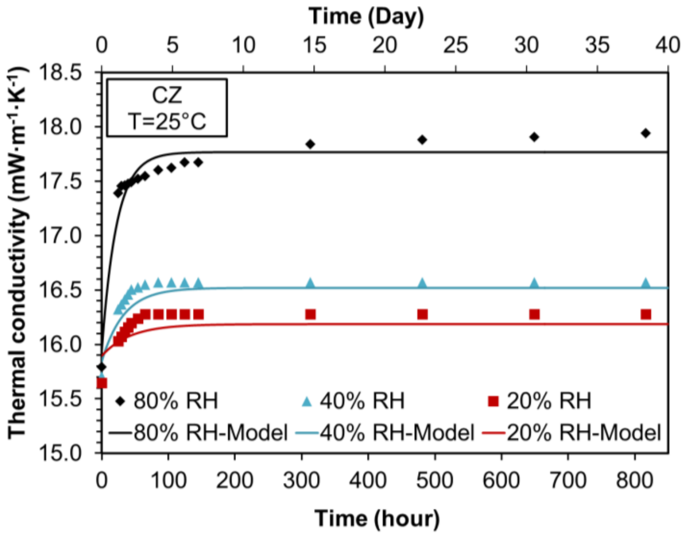

Figure 6. Thermal conductivity of CZ over time at 25°C and 20%, 40% and 80% RH

Figure 6 shows that it took about 20 hours 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.
Values of diffusion coefficient (*D)* and time constant (τ) are shown in Table 3. 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.

Table 3. Diffusion parameters of CZ at different RH

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

4.3 Steady-state condition thermal conductivity analysis

The thermal conductivity of each pair of samples was measured in TPS with a power of 10 mW, measurement time of 40s and rest interval of 24 hours between measurements to ensure steady state condition. Figure 7 presents the effective thermal conductivity of aerogel blanket samples as a function of RH at two temperatures of 25°C and 45°C.

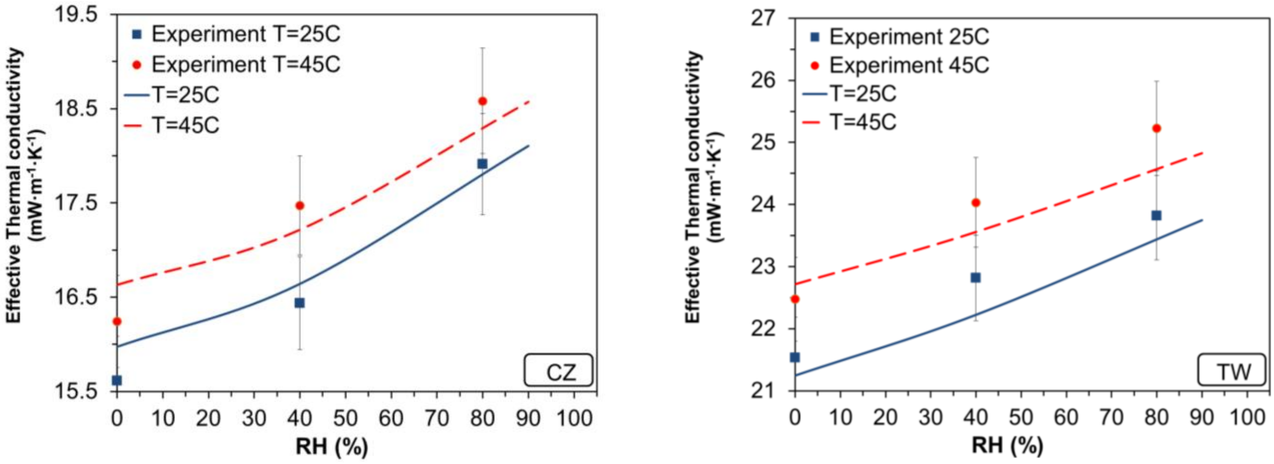

Figure 7. Effective thermal conductivity as a function of RH for CZ (left) and TW (right) at 25°C and 45°C

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 Figure 7, the modelling 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 Figure 5), which leads to a sharper thermal conductivity increase at 25°C.

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.

6. References

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