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Aerogel blankets: From mathematical modeling to material characterization and experimental analysis

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ABSTRACT

One of the most feasible solutions for reducing the global energy consumption and associated CO_2 emissions, is through usage of more efficient insulation systems in buildings and refrigeration units. Commercialization of high-performance thermal insulation will significantly contribute to environmentally sustainable future development. Aerogel composites provide superior thermal resistance and enable new design approaches for high performance insulation systems. This paper presents a theoretical and experimental study on the effective thermal conductivity of aerogel composites. The analytical model represents aerogel composites with a unit cell consisting of a cylindrical fiber surrounded by a packed bed of aerogel particles. The model accounts for various heat transfer mechanisms, namely conduction in the solid, gas conduction, and radiation. The properties and microstructure of two types of aerogel composites (Cryogel® Z and ThermalWrap™) were studied with scanning electron microscopy (SEM), mercury intrusion porosimetry (MIP), and Fourier transform infrared spectroscopy (FTIR). The apparent thermal conductivity of the samples of aerogel blanket were measured using heat flow meter (HFM) at mean temperature ranging from −20 °C to 80 °C and the results polished thorough two-thickness method to de-convolute the effect of thermal contact resistance (TCR), between the sample and HFM hot and cold plates, from the apparent thermal conductivity values. The effective thermal conductivity results were found to increase from 0.0135 to 0.0175 W m^{-1} K^{-1} for Cryogel® Z and 0.0188 to 0.0271 W m^{-1} K^{-1} for ThermalWrap™ at mentioned temperature range. The analytically predicted variation in the effective thermal conductivity as a function of temperature agreed well with the experimental data. Using the proposed model, parametric studies were performed to investigate the effect of blanket porosity and fiber thermal conductivity on the effective thermal conductivity of aerogel composites.

1. Introduction

Commercial and residential buildings are a large source of energy consumption. In 2012, an estimated 18.9 quadrillion BTU were consumed in the residential and commercial sectors of the United States, representing about 1/5 of total energy used [1] and data from 2009 suggests that 48% of home energy use in the U.S. was for thermal comfort [2]. Retrofit insulation is one of the most time/cost-effective approaches that are extensively used in industrial and residential installations to reduce the energy losses for heating and cooling systems. As such, development of high performance thermal insulation materials is a key to save space and energy consumption, increase comfort, and decrease cost and complexity. Among available insulating material categories, e.g. foamy, fibrous and powder, aerogels are a promising high performance type for both stationary and mobile applications.

Aerogels are prepared through a supercritical drying process that creates a highly porous open cell solid material that features thermal conductivities as low as 0.013 W m^{-1} K^{-1} [3]. Their remarkable properties include extremely low thermal conductivity, high resistance to acoustic waves, and low dielectric constant. Aerogels function as thermal super insulators mainly by minimizing heat conduction through their low density and tortuous solid nanostructure; heat convection through very small pore sizes (approximately 10 nm, which is about 8 times smaller than air molecular free path [4]); and radiation by adding infrared (IR) absorbing or scattering agents in the aerogel matrix. Super-insulating silica-based aerogels are low density, typically in the range of 0.08–0.2 g cm^{-3}, nanostructured solids with high porosity (>90%) and typical mesopore diameters between 4 and 20 nm. However, aerogels have a delicate structure with low compressive strength and high susceptibility to fracture, which makes them

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Nomenclature

d	diameter (m)
e_b	blackbody emissive power
k	thermal conductivity (W m^{-1} K^{-1})
K_R	mean extinction coefficient
L	thickness of the sample (m)
n	index of refraction
$\dot{q}$	heat flux (W m^{-2})
R_{total}	total resistance
r	radius (m)
T	temperature (K)
$T_{n\lambda}$	spectral transmittance
V	volume (m^3)

Greek symbols

α	deformed factor
β	extinction coefficient
ε	porosity
λ	wavelength (m)
σ	Stefan–Boltzmann constant

Subscripts

app	apparent
b	blanket
cond.	conduction
eff	effective
f	fiber
g	gas
gs	gas solid region
m	medium
s	solid
rad.	radiation

difficult to handle. They are also prone to settling over time, especially when exposed to vibration or thermal cycling. The settling process can form voids and lead to heat leakage in the void spaces, which is a major drawback for any powder-based insulation [5]. Therefore, more durable aerogel composites, known as fiber-reinforced aerogel blankets, have been developed. These materials have applications in aerospace, military cryogenic applications, oil and gas processing industry, and construction [6].

Aerogel blankets contain aerogel particles, fibers and optionally, a binder. The material is mechanically stable and has low thermal conductivity ranging between 0.017 and 0.04 W m^{-1} K^{-1} [7].

SEM images shown in Fig. 1, illustrate the microstructure of Cryogel® Z and ThermalWrap™ aerogel blankets in which fibers are coated with amorphous silica aerogel particles and there are voids between the coated fibers. Cryogel® Z contains polyethylene terephthalate (PET)/fibrous glass, while ThermalWrap™ contains bicomponent fibers with a polyethylene terephthalate (PET) core and a copolyolefin sheath. The manufacturers claim that there are no fiber–fiber contacts within the aerogel–fiber composite matrix that would allow solids heat conduction through aerogels [5]. This structure of aerogel blanket alleviates the handling problems (mechanical strength) of aerogel powders while reducing the heat transfer rate through fibrous matrix. Additionally, closely packed aerogel particles on the fibers suppresses gas conduction heat transfer by reducing the void spaces between fibers resulting in higher thermal resistance that is achieved in both evacuated and non-evacuated systems [5].

The porous nature of aerogel blanket makes it necessary to define an effective thermal conductivity in order to predict its *R*-value under various operating conditions and optimize its thermal performance in new designs. To the best of our knowledge, there are only few studies are available in the open literature on thermal performance modeling of aerogel blankets; a summary of the literature is presented in Table 1.

As shown in Table 1, there is a lack in the literature for compact analytical relationship capable of predicting the thermal conductivity of aerogel blankets, which is supported and verified thorough experimental studies that capture the ranges of low temperature to high temperature conditions for different structured samples. Hence, in this paper, the goal is developing an analytical model for predicting the thermal conductivity of aerogel blankets. Experimental tests have been performed to provide the input properties of the model as well as experimental values of thermal conductivity in various temperatures for validating the model for different samples.

In this paper, for thermal conductivity modeling, a unit cell based approach is followed in which the basic cell structure representing the aerogel blanket media is presumed to be repeated

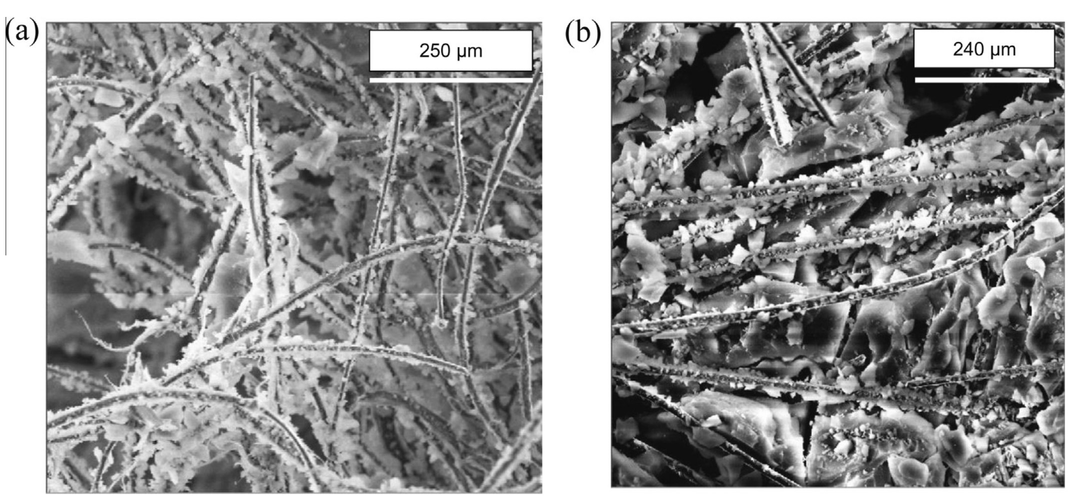

Fig. 1. SEM images of (a) ThermalWrap™ aerogel blanket and (b) Cryogel® Z.

Table 1
Summary of literature on aerogel composite insulation performance.

Author(s)	Notes
Oh et al. [8]	• Synthesized PET/aerogel blanket
	• Performed experimental study on PET/aerogel blanket
	• No closed form solution/analytical modeling
	• No numerical modeling
Coquard et al. [9]	• Performed numerical modeling of conductive heat transfer inside nano-structured silica based materials
	• No experimental study
	• No closed form solution/analytical modeling
Wei et al. [10]	• Synthesized xonotlite–aerogel composite
	• Performed experimental study on xonotlite–aerogel composite
	• Proposed an analytical model for conduction and radiation heat transfers using unit cell approach (k value reported of 0.028–0.10 W m^{1} K^{-1} for 300–800 K)
	• Verified for low temperature ranges
	• No numerical modeling
Alvey [11]	• Performed experimental study on four different samples of aerogel composites
	• Proposed an analytical model for conduction and radiation heat transfers
	• No numerical modeling
Gupta [12]	• Synthesized aerogel/epoxy composites
	• Performed experimental study of the compressive loading conditions on aerogel/epoxy composites
	• No closed form solution/analytical modeling
	• No numerical modeling
Xie et al. [13]	• Analytical modeling of conduction and radiation heat transfers using unit cell approach (k value reported of 0.03–0.28 W m^{-1} K^{-1} for 300–1400 K)
	• No verification for low temperature ranges
	• No experimental study
	• No numerical modeling

throughout the blanket. Using the observations of SEM imaging, the proposed unit cell is assumed to be a 'packed bed' of spherical aerogel particles with more than 90% porosity and a solid cylindrical fiber at the center. A new analytical model for predicting the thermal conductivity of aerogel blankets is proposed and validated, for two types of aerogel blankets, with two different thicknesses of each, using HFM. Two-thickness method is followed to drive the effective thermal conductivity of each type of samples and eliminate the thermal contact resistance effect between the HFM hot and cold plates and the sample. Moreover, a parametric study is performed to investigate the effect of key parameters on the effective thermal conductivity of aerogel blankets.

2. Model development

The proposed geometrical model for the unit cell approach is shown in Fig. 2. It consists of two domains: a rigid solid cylindrical fiber; and a spherical aerogel packed bed around it, both into a noticeable void space.

The assumptions used in the model development are listed below:

- Steady-state one-dimensional heat transfer in the medium.
- Negligible natural convection due to small pore sizes (<4 mm); one can calculate the Rayleigh number based on the pore size to be $Ra \sim 10^{-10}$,which is significantly lower than 1708, which is the threshold for natural convection to be a considerable contributing mechanism in enclosures [10].
- Smooth spheres and fiber surfaces, i.e., no roughness between contacting spheres and the fiber.
- No heat generation source in the medium.

Therefore, the unit cell modeling consists of two parts: (1) solid and gas conduction heat transfer modeling of the cylinder and its surrounding medium, and (2) radiation heat transfer modeling of the unit cell, which are presented in the following sub-sections.

2.1. Conduction heat transfer

Conduction heat transfer in the unit cell is a function of the fiber and medium thermal conductivities. Following [14], a compact relationship for thermal conductivity of an infinite cylinder (fiber) in an infinite medium (aerogel packed bed) with a linear temperature gradient can be developed.

The summary of the equations that lead to the final relationship for conduction heat transfer is presented below:

$$\frac{T}{T_f} = \left[1 - \frac{k_f - k_m}{k_f + k_m}\left(\frac{r_f}{r}\right)^2\right] Z \qquad Z = \frac{z}{r_f} \qquad z = r\cos(\theta) \tag{1}$$

where k_f and k_m are thermal conductivities of the fiber and its surrounding medium, respectively. r_f is the fiber radius and d is the unit cell length that is calculated using following equation:

$$\varepsilon_b = \frac{V_{void}}{V_{total}} = \frac{\left(d^2 - \pi r_f^2\right)\varepsilon_m}{d^2} \tag{2}$$

Here, V_{void} is the volume of the unit cell empty spaces and V_{total} is the total volume of the unit cell, and ε_b and ε_m are blanket and medium porosities, respectively. In this study, blanket porosity is measured by mercury intrusion porosimetry (MIP) and the porosity of aerogel packed bed exists in the literature [15] as the medium, so that unit cell length has been calculated afterwards using Eq. (2).

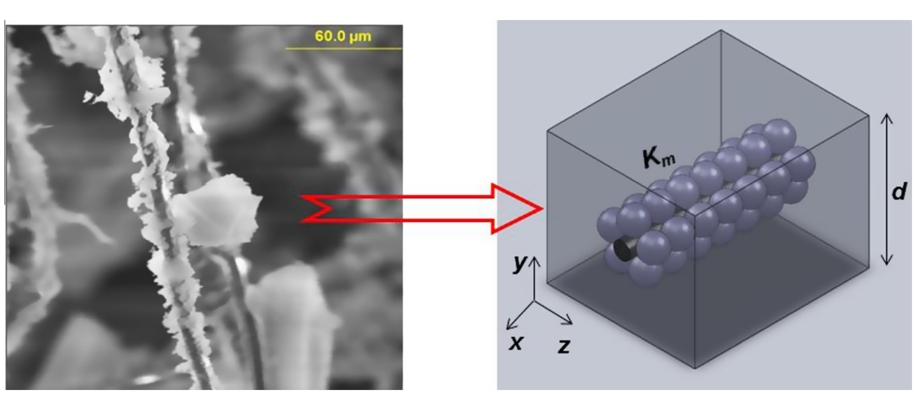

Fig. 2. Proposed unit cell for aerogel blanket geometrical modeling.

Having the temperature distribution in the proposed unit cell, an effective conduction heat transfer coefficient of the blanket can be calculated using Eq. (3):

$$k_{cond.} = \frac{k_m \frac{\partial T}{\partial z}\big|_{\frac{d}{2}}}{\frac{\Delta T|^{\frac{d}{2}}_{-\frac{d}{2}}}{d}} \tag{3}$$

Simplifying Eq. (3) yields a compact relationship for the contribution of the conduction heat transfer in the effective thermal conductivity of the blanket

$$k_{cond.} = \frac{k_m\left[4\sqrt{2}\left(\frac{r_f}{d}\right)^2(k_f - k_m) + 1.77(k_f + k_m)\right]}{-4\sqrt{2}\left(\frac{r_f}{d}\right)^2(k_f - k_m) + 1.77(k_f + k_m)} \tag{4}$$

In Eq. (4), k_m is the aerogel packed bed thermal conductivity as the medium around the fiber, which consists of gas heat conduction (inside the pores) and heat conduction through spherical aerogel particles. Different approaches can be used to obtain the thermal conductivity of a bed of spheres filled with a stagnant gas, which can be categorized into two main divisions: numerical and analytical approaches. Buonanno and Carotenuto [16] used a three-dimensional FEM (Finite Element Analysis) model to calculate the thermal conductivity of simple cubic and body center cubic packed beds. Buonanno et al. [17,18] measured the effective thermal conductivity of uniformly-sized rough stainless steel spheres. Their FEM numerical modeling results are in good agreement with the experimental data. Analytical models for calculating the effective thermal conductivity of the unit cells of packed beds of uniformly sized spheres have been established by Ogniewicz and Yovanovich [19] and Turyk and Yovanovich [20] and verified with experimental data. Bahrami et al. [21] also developed a model for predicting the effective thermal conductivity of packed bed of rough spheres and implemented contact mechanic and thermal analyses to present the results as a compact relationship. Wei et al. [22] evaluated the thermal conductivity of silica aerogel powder as an insulation material. They measured gaseous conductivity values from very low pressures up to the ambient pressure and showed its dependence on pressure. In this paper, Zehner–Schlunder [23] modified model for spherical packed beds has been followed to calculate the thermal conductivity of the medium. They assumed that heat transfer occurs through two parallel paths, as they showed in their unit cell: (i) the gas region (air with $Kn < 0.1$) and (ii) solid and gas regions. Therefore, following [23], the thermal conductivity of the medium is given by Eq. (5):

$$k_m = \left(1 - \frac{1}{R'^2}\right)k_g + \left(\frac{1 - r_s^2}{R'^2}\right)k_{gs} + \left(\frac{r_s}{R'}\right)^2 k_s \tag{5}$$

k_{gs} is the equivalent thermal conductivity of the region that consists of gas and solid phases, R' is the radius of packed bed unit cell, r_s is the radius of contact area, and k_g and k_s are the gas (air) and solid (silica aerogel) thermal conductivities, respectively. The unit cell radius, R', is also obtained from Eq. (6), in which ε_m is the medium effective porosity:

$$\frac{1}{R'^2} = \sqrt{(1 - \varepsilon_m)} \tag{6}$$

And radius of the contact area, r_s, is determined by Eq. (7); where α is the deformed factor. This parameter is difficult to measure experimentally. Therefore, in this work it is used as a fitting parameter and its value is assumed $\alpha = 0.1$.

$$r_s = 1 - \frac{1}{(1+\alpha)^2} \tag{7}$$

Assuming that the thermal resistances of the solid and gas phases are in series with respect to the temperature gradient, the resulting relationship for k_{gs} is:

$$\frac{k_{gs}}{k_g} = \frac{2}{1-\zeta}\left(\frac{1}{1-\zeta}\ln\left(\frac{1}{\zeta}\right) - 1\right) \tag{8}$$

$$\zeta = \frac{k_g}{k_s} \tag{9}$$

ζ is the ratio of gas thermal conductivity to solid thermal conductivity $\left(\frac{k_g}{k_s}\right)$. Here, the model is modified to include the gas rarefaction effects. Therefore, k_g is defined as following:

$$k_g = \frac{k_{g_0}}{1 + 2\xi Kn} \tag{10}$$

k_{g_0} is the temperature dependent gaseous conductivity at atmospheric pressure, which is calculated as below:

$$k_{g_0} = 0.0021 + 8 \times 10^{-5} T\ (\mathrm{K}) \tag{11}$$

ξ is a constant specific to the gas in the pores, for air $\xi \cong 2$. Kn is the Knudsen number defined as $Kn = \frac{\Lambda_m}{d_p}$, d_p is the characteristic system size, is the mean pore size of the blanket in this work. Λ_m is the mean free path of gas molecules in free space, calculated as

$$\Lambda_m = \Lambda_{m_0}\frac{P_0}{P}\frac{T}{T_0} \tag{12}$$

Λ_{m_0} is in standard condition (69 nm), P_0 and T_0 are standard pressure and temperature, respectively, which is 1 atm and 298 K.

2.2. Radiation heat transfer

A portion of heat transfer through aerogel blankets is due to radiation. When a material is optically thick, such as in a 1 cm thick insulation layer, radiation travels only a short path before being scattered or absorbed. In this situation, radiative heat transfer can be modeled using the Fourier heat conduction law and it is called the diffusion approximation method [24]. The corresponding radiative thermal conductivity, k_r, can be found from Eq. (13):

$$k_{rad} = \frac{16\sigma n^2 T^3}{3K_R} \tag{13}$$

In Eq. (13), $\sigma = 5.67 \times 10^{-8}\ \mathrm{W\,m^{-2}\,K^{-4}}$ is Stefan–Boltzmann constant, n is the index of refraction, and K_R is the Rosseland mean extinction coefficient of the blanket. The extinction coefficient shows the deterioration rate of the radiation intensity passing through the material. The Rosseland mean extinction coefficient is defined as Eq. (14) [24]:

$$\frac{1}{K_R} = \frac{\int_0^\infty \frac{1}{\beta_\lambda}\frac{\partial e_{b\lambda}}{\partial T}d\lambda}{\int_0^\infty \frac{\partial e_{b\lambda}}{\partial T}d\lambda} = \int_0^\infty \frac{1}{\beta_\lambda}\frac{\partial e_{b\lambda}}{\partial e_b}d\lambda \tag{14}$$

where λ is the wavelength, T is the medium temperature, e_b is the blackbody emissive power, $e_{b\lambda}$ is the spectral black body emissive power, and β_λ is the spectral extinction coefficient. The spectral extinction coefficient for a thin sample can be obtained by using Beer's law [24].

$$\beta_\lambda = -\frac{\ln(T_{n\lambda})}{L} \tag{15}$$

$T_{n\lambda}$ is the spectral transmittance and L is the thickness of the sample. In this study, the spectral transmittance was measured for two types of aerogel blankets for the wavelength range of 2.5–40 μm (Fig. 4) using a Fourier transform infrared spectrometer (FTIR), which model is Shimadzu-IR Prestige-21.

As mentioned in the assumption, total heat transfer through the unit cell consists of conduction and radiation heat transfers, which for both of them coefficients are defined and modeled (Eq. (16)). Presented in Eq. (17) is the final relationship for the effective thermal conductivity of the insulation material that is obtained by superposition of the conduction and radiation thermal conductivities following [10]:

$$k_{eff} = \frac{Q_{tot}}{\Delta T \cdot d} = \frac{Q_{cond.} + Q_{rad.}}{\Delta T \cdot d} \quad (16)$$

$$k_{eff} = k_{cond.} + k_{rad.} \quad (17)$$

3. Experimental study

In this paper, samples of aerogel blanket produced by two manufacturers, Aspen Aerogels Inc. and Cabot Co., are investigated. Table 2 shows the specifications of the samples in terms of what manufacturers reported and what are tested by the authors in this study.

Fig. 3 is a simple schematic of heat flow meter (HFM), Netzsch HFM 436 Lambda, which is used for measuring the thermal conductivity of the insulation samples (0.002–2 W m^{-1} K^{-1}). The instrument has been calibrated with a NIST-certified reference standard of known thermal conductivity. The tests are conducted as per ASTM C518 standard. The sample is sandwiched between two metallic plates with a controlled temperature gradient, and mechanical load (pressure) control. The allowable range for implementing thermal conductivity tests using this device is −40 to 100 °C (on the plates), therefore, in the present study, tests are performed with mean temperatures ranging from −20 to 80 °C, temperature gradients of 40 °C and following ASTM C177, fixed pressure load of 0.5 psi. In HFM, sensors measure the heat flux and thermocouples measure the hot and cold plate temperatures. The HFM signal, Q (μV), is proportional to the heat flux $\dot{q}$ across the sample, which is proportional to temperature difference, ΔT, between the plates and inversely proportional to the total thermal resistance, R_{total}:

$$\dot{q} = -k\frac{\Delta T}{\Delta x} = \frac{\Delta T}{R_{total}} \quad (18)$$

To determine the resistance of the samples, thermal contact resistance (TCR) between the samples and the plates needs to be eliminated from the total resistance value, which is the output of HFM. For the accurate measurement of the bulk resistance as well as thermal conductivity, two-thickness method [25] is usually employed by testing two samples of the same material, under the same pressure but with different thicknesses (t_1 and t_2). The total value of the thermal resistance for each sample can be written as Eq. (19):

$$R_{tot_i} = R_{bulk_i} + 2\mathrm{TCR}, \quad i = 1,2 \quad (19)$$

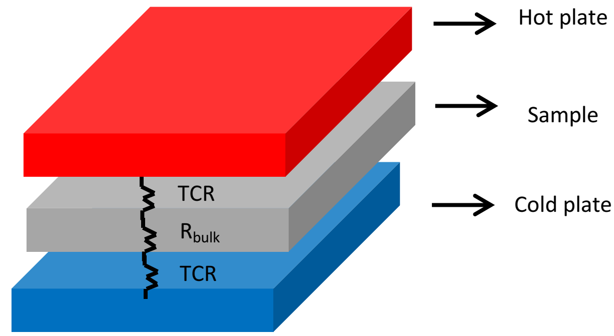

Fig. 3. Simplified schematic of a heat flow meter and its thermal resistance network.

Table 3
Aerogel blanket thermal conductivity test results in various conditions with 40 °C temperature gradient.

Condition #	Mean T (°C)	Cryogel® Z thermal conductivity (W m^{-1} °C^{-1})	ThermalWrap™ thermal conductivity (W m^{-1} °C^{-1})
1	−20	0.0147	0.0188
2	−10	0.0148	0.0196
3	0	0.0151	0.0203
4	10	0.0154	0.0210
5	20	0.0155	0.0217
6	30	0.0157	0.0224
7	40	0.0159	0.0228
8	50	0.0161	0.0244
9	60	0.0164	0.0253
10	70	0.0163	0.0259
11	80	0.0165	0.0271

$$R_{bulk_i} = \frac{t_i}{k \cdot A}, \quad i = 1,2 \quad (20)$$

where k represents the thermal conductivity and A is the surface area of the sample that is in contact with the plates. TCR represents the thermal contact resistance between the samples and hot and cold plates, which does not depend on the thickness of the samples. In Eq. (19) R_{tot} is the only measurable resistance (Fig. 3). Therefore, the thermal conductivity of the samples k-value and TCR can be obtained by solving Eqs. (21) and (22), respectively.

$$k = \frac{t_2 - t_1}{A(R_{tot_2} - R_{tot_1})} \quad (21)$$

$$\mathrm{TCR} = \frac{t_2 R_{tot_1} - t_1 R_{tot_2}}{2(t_2 - t_1)} \quad (22)$$

The mentioned test conditions applied to the samples of aerogel blanket and the results are presented in Table 3. Each sample is tested for three times with the same temperature conditions; the standard deviations are less than 10^{-4} W m^{-1} °C^{-1}.

Table 2
Aerogel blanket samples specifications.

Sample	Provider	Thickness	Density	Fiber composition	Powder material	Thermal Conductivity (@ RT)
(a) Manufacturer data [4,7]						
Cryogel® Z	Aspen Aerogels Inc.	10 mm 5 mm	130 kg m^{-3}	Polyester/fiber glass	Silica (SiO_2)	0.014 W m^{-1} K^{-1}
ThermalWrap™	Cabot Corp.	8 mm 5 mm	70 kg m^{-3}	Polyester and polyethylene	Silica (SiO_2)	0.023 W m^{-1} K^{-1}

Sample	Provider	Powder diameter	Fiber diameter	Porosity	Extinction coefficient
(b) Measured values					
Cryogel® Z	Aspen Aerogels Inc.	10 μm	20 μm	91%	4014 m^{-1}
ThermalWrap™	Cabot Corp.	4 μm	7 μm	79%	3165 m^{-1}

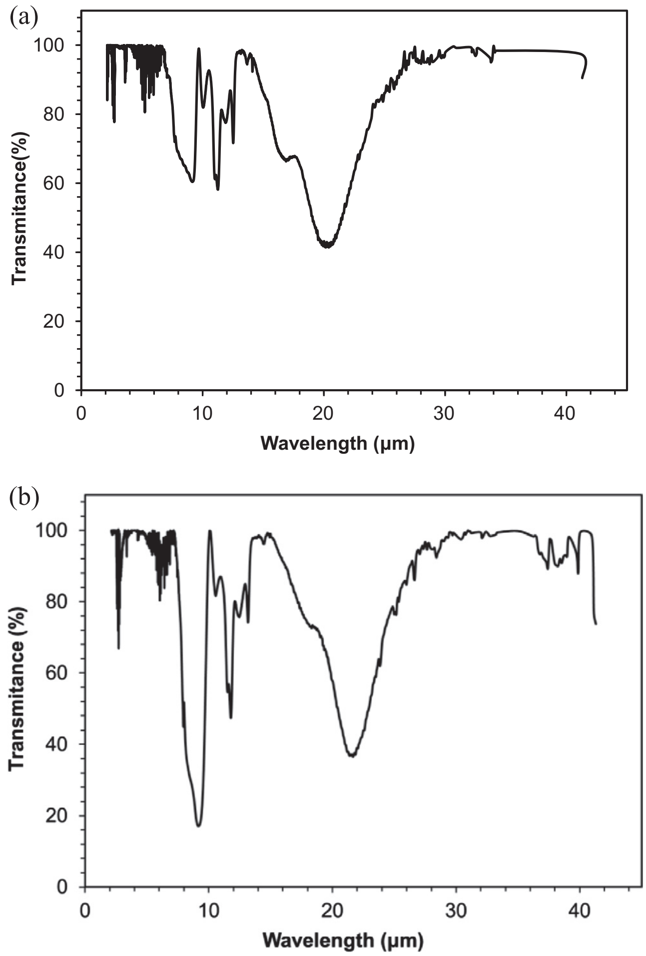

Fig. 4. Spectral transmittances of (a) Cryogel® Z, and (b) ThermalWrap™.

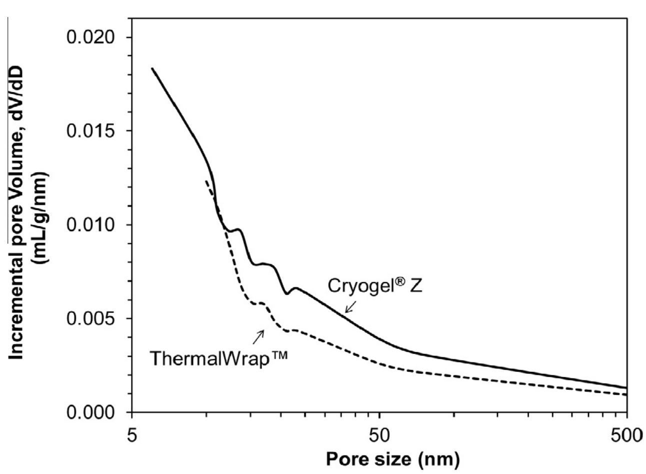

Fig. 5. Pore size distributions of Cryogel® Z and ThermalWrap™.

The extinction coefficients of both aerogels are determined from their spectral transmittance measured using a FTIR spectrometer, and shown in Fig. 4(a) and (b). The extinction coefficients were subsequently calculated by Eq. (14).

The porosity of the samples is measured by the mercury intrusion porosimetry (MIP) method using a mercury intrusion porosimeter (AutoPore IV, Micromeritics Instrument Corporation). The pore size distributions for Cryogel® Z and ThermalWrap™ are shown in Fig. 5.

4. Result and discussion

The proposed mathematical model is solved using MATLAB [26], which enables parametric studies and analysis. In the following section, a comparison of modeling results and the experimental data is provided followed by parametric studies in which the effects of fiber thermal conductivity and the blanket porosity on the effective thermal conductivity of aerogel blanket are examined.

4.1. Model validation and parametric studies

Fig. 6 presents the variation of the effective thermal conductivity of Cryogel® Z and ThermalWrap™ over a temperature range of −20 °C to 80 °C. The highlights of Fig. 6 are:

- Higher temperature leads to higher thermal conductivity.
- By increasing the temperature from −20 °C to 80 °C, the effective thermal conductivity increases approximately 12% for Cryogel® Z and 44% for ThermalWrap™, which is due to higher radiation and gas conduction heat transfers and obviously is way more for ThermalWrap™ compared to Cryogel® Z.
- The effective thermal conductivity of Cryogel® Z is less than ThermalWrap™, which was consistent with manufacturer data sheet. It is because of lower thermal conductivity of fibers and smaller blanket pore sizes in this composite.

Fig. 7 shows a comparison of the contribution for each heat transfer mode in the effective thermal conductivity of Cryogel® Z and ThermalWrap™. It reveals that the major portion (about 95%) of the total thermal conductivity is due to the conduction (gas and solid). It should be noted that this contribution decreases with increasing temperature because the radiation contribution rises and this effect is more prominent in ThermalWrap™ samples.

The developed model can be conveniently used to systematically study the effect of aerogel blanket microstructural parameters, thermo physical properties, and operating conditions on its effective thermal conductivity. The important parameters that produce noticeable variations in the effective thermal conductivity are fiber thermal conductivity and porosity of the blanket. The objective is to investigate optimized values for such parameters, which can lead to new designs of aerogel composites with lower effective thermal conductivity. As shown in Fig. 8, fibers thermal conductivity, as one of the influential factors in the aerogel blanket structure, has a minor effect on the effective thermal conductivity of the blanket, keeping the other parameters constant. This analysis provides more appropriate options for choosing low thermally conductive fibers along with cost and availability.

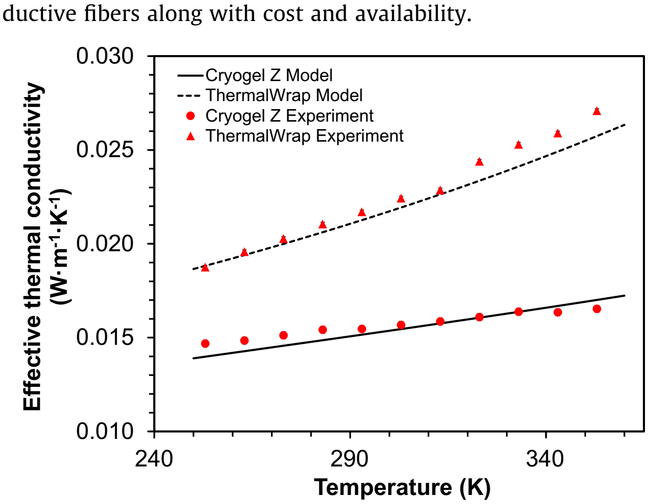

Fig. 6. Temperature dependence of the thermal conductivity of Cryogel® Z and ThermalWrap™ aerogel blankets.

Fig. 9 highlights are:

- The lower the blanket porosity, the higher the effective thermal conductivity.
- By decreasing the blanket porosity from 90% to 70%, the thermal conductivity increases about 40%, which is prominent.

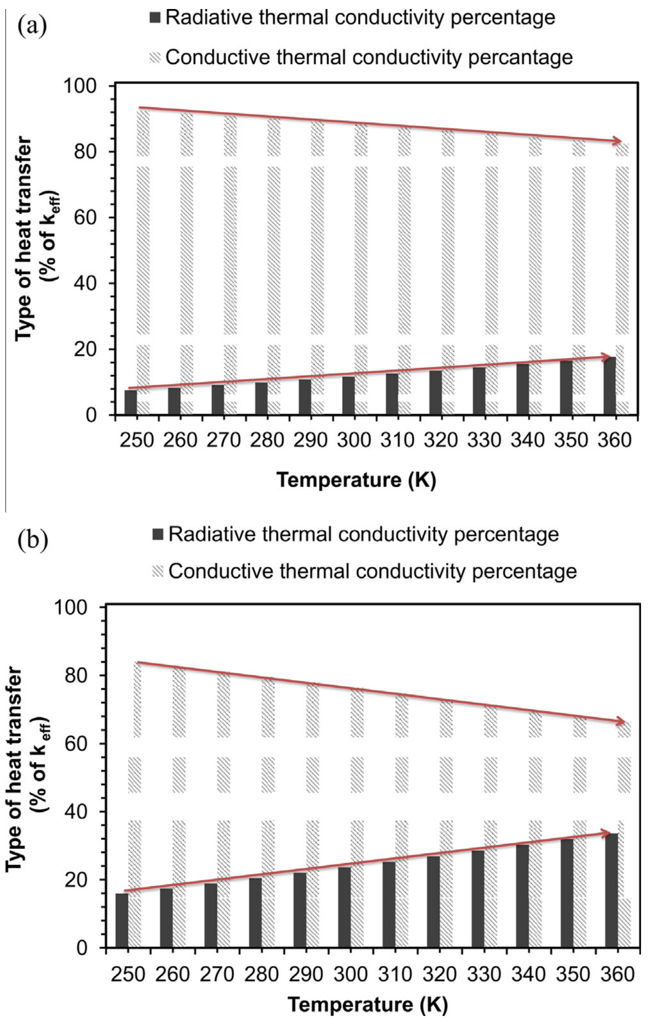

Fig. 7. Contribution of each type of heat transfer (%) on effective thermal conductivity; (a) Cryogel® Z aerogel blanket, (b) ThermalWrap™ aerogel blanket.

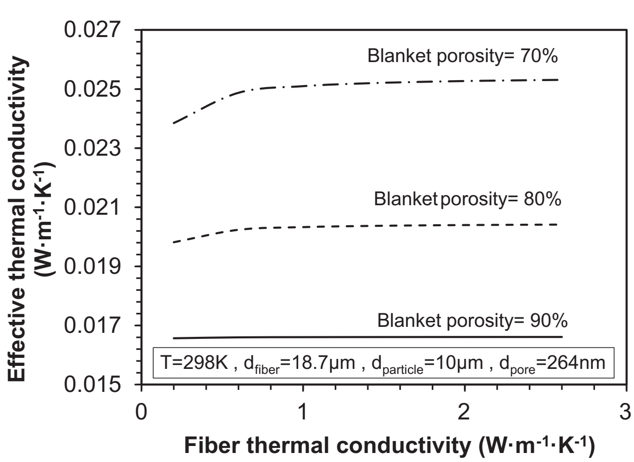

Fig. 8. Fiber material thermal conductivity effect on the effective thermal conductivity.

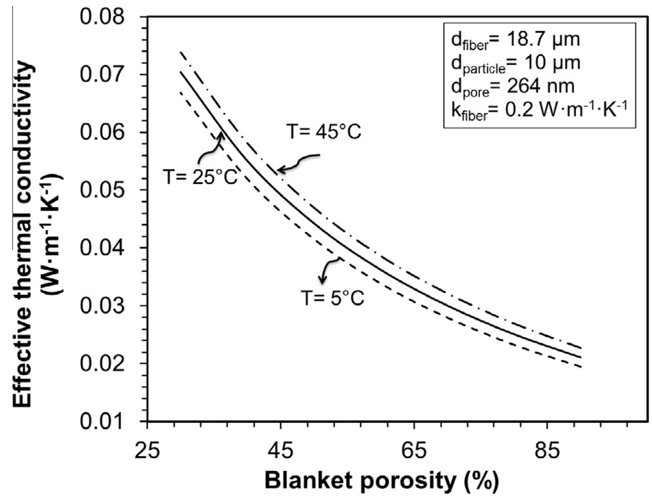

Fig. 9. Effect of blanket porosity on the effective thermal conductivity.

It should be noticed that high blanket porosity can be interpreted as a few *large sized* pores or lots of *small sized* pores. Larger pore sizes create larger gaps for conduction heat transfer through gas molecules and the effective thermal conductivity increases when there are larger pores in the blanket. On the other hand, larger pore sizes result in higher porosity which might be a factor for less effective thermal conductivity. This issue is addressed in aerogel blanket by creating large surface areas in combination with nano-porous pathways. Hence, high porosity, small pore sizes and large surface area are key to low thermal conductivity in aerogel blankets.

Low thermal conductivity in aerogel blankets is due to its nature as a highly porous solid material, which means almost no gas convection, very small gas and solid conduction and small radiation heat pathways. Hence, as it can be understood from Fig. 9, reducing the porosity eliminates the leverage of using aerogel blankets as an insulation material and in this case using the other conventional types of insulations may be more prudent.

5. Conclusion

The thermal conductivity of aerogel blanket insulation material was investigated theoretically and experimentally for two specific samples, Cryogel® Z and ThermalWrap™. The analytical model followed the unit cell approach, assuming a repeated pattern in the aerogel blanket structure. A compact relationship was proposed for the effective thermal conductivity, which accounted for solid and gas conduction as well as thermal radiation, and was validated with experimental data, which has been polished through two-thickness method. The modeling results show that the highly porous structure of aerogel blanket and micro-scale pore sizes as well as large surface areas are the key features that make the aerogel blanket as an effective insulation material having very low thermal conductivity. Temperature study of aerogel blanket effective thermal conductivity showed that this property is lower than many other conventional types of insulation material in a wide range of temperatures. Low rate of heat transfer as well as slight thickness and mechanical stability make aerogel composites a promising option for insulating all types of enclosures using different types of them in terms of fiber-aerogel combination.

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