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Feasibility study of novel integrated aerogel solutions

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Abstract

The market share for fibre reinforced aerogel insulation materials is expected to increase as production costs are lowered, and in this context, the development of layered products with integrated aerogel is highly interesting. The effect of uniaxial compression and humidity on the thermal conductivity of commercially available aerogel insulation blankets were measured in order to assess the feasibility of integrating aerogel blankets with other building components. The thermal performance under uniaxial compression was measured by compressing commercially available aerogel blanket materials in a heat flow meter apparatus. Up to 11.5 % decrease in apparent thermal conductivity was observed at a compressive strain of 16 %, corresponding to an applied stress of approximately 22 kPa. The thermal insulation properties of the aerogel insulation blankets remained excellent within the range of compressive stress investigated in this study (up to about 40 kPa), making aerogel integration highly interesting for building components that will be used under compression. However, a 32 % increase in thermal conductivity was observed upon exposure to an atmosphere of 95 % relative humidity (RH). Thus, in order to widen the range of application for fibre reinforced aerogel insulation materials, further investigations should be conducted to understand and improve their tolerance to moisture.

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Keywords: aerogel; integrated products; thermal conductivity; moisture; uniaxial compression

1. Introduction

Aerogels are among the best thermal insulation materials available on the market today. They are the only fire resistant materials that offer thermal conductivity values as low as 0.012 – 0.018 W/(mK) without the need for vacuum or gas sealed systems [1]. The main disadvantages are high production costs and low tensile strength, hence making aerogel insulation materials more expensive and difficult to apply as compared with several conventional insulation materials. Thus, the use of aerogel in buildings have mainly been limited to thermal barriers at thermal bridges and in

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glazed facades. However, aerogels are ideal for projects where space limitation is of essence, such as retrofitting old buildings and roof/floor/wall constructions in highly populated areas.

There are a handful of fibre reinforced aerogel insulation materials available on the commercial market, and the market share is expected to increase as production costs are lowered [2, 3]. In this context, the development of layered products with integrated aerogel is highly interesting. Aerogel insulation may be laminated to wind barriers or incorporated into products such as window frames and masonry blocks. This has the added advantages of providing a substrate to compensate for the low aerogel tensile strength and reducing the number of operations required on the construction site. In this work, we have investigated selected properties of commercially available aerogel insulation blankets that are of importance for fabrication of integrated aerogel solutions; strain and thermal conductivity during uniaxial compression, and the effect of humidity on the thermal conductivity.

State-of-the-art triple/quadruple glazed windows have rather low thermal transmittance (U) values both for the window frames and the glazing systems, where often the glazing systems have the lowest U-values. Thus, solutions that improve the thermal insulation properties of the frames may lead to an enhancement in the overall thermal performance of the windows. Simulations have shown that employing materials with thermal conductivity < 0.02 W/(mK) as thermal breaks and insulation between components may be an effective optimization strategy to improve the thermal properties of window frames [4, 5]. Furthermore, replacement of existing polymeric thermal break materials with fire-resistant and more environmental-friendly materials will be an important aspect. Similarly, thermally insulating masonry blocks could be improved by aerogel insulation integration in cavities or layers. Mechanical properties and thermal insulation properties under compression and in moist conditions are important factors in the consideration of insulation materials in e.g. window frames and masonry blocks.

Bardy et al. [6] compared the effect of hydrostatic pressure on deformation and thermal conductivity of a prototype to that of a commercially available aerogel insulation blanket. Hoseini et al. [7] investigated the deformation and thermal resistance of two commercially available aerogel blanket insulation materials under uniaxial compression. The latter reported a density increase of ~10 % at a uniaxial pressure of ~3 kPa, resulting in a thermal resistance reduction between 4 to 8 %. The effect of compression on thermal conductivity may vary significantly between products, and thus more research is needed to get an understanding of this property.

The effect of moisture on the thermal conductivity of aerogel granules has been shown to be insignificant in a previous study [8]; however, a recently published article reports that the thermal conductivity of aerogel insulation blankets may increase up to 40 % when exposed to an atmosphere with 90 % relative humidity (RH) [9]. The difference of moisture effect on these two aerogel products was remarkable, and thus more research should be conducted in order to assess if the type of aerogel product has this much of an impact on performance in high moisture atmospheres. This is of vital importance in applications where the insulation material is at a risk of elevated moisture levels.

2. Experimental

2.1. Materials

Commercially available aerogel blanket materials are essentially composite materials consisting of silica aerogel, glass/polymer fibres and carbon black. Typically, the mats are prepared by infusing a fibre fleece support with silica precursor sol, which is then gelled and dried under conditions that lead to aerogel formation. Graphite is typically added to reduce radiative heat transfer. Alternatively, solid insulation mats can be prepared by compacting aerogel particles with finely dispersed fibres and an organic binder [3]. They are usually supplied in the form of rolls or batts, and have colours ranging from white to dark grey depending on the amount of graphite added.

Three different product-line aerogel insulation blankets were investigated in this work. For the purpose of differentiation without identifying the product brand, they were designated aerogel blanket (AB) 1, 2 and 3. Some key properties of the studied materials are listed in Table 1.

Table 1. Selected properties of commercial aerogel insulation blankets.

Aerogel blanket	Thickness h (mm)	Colour	Form	Covering
AB1	10	dark grey	roll	none
AB2	~18	dark grey	batt	none
AB3	~10	dark grey	batt	cloth

2.2. Characterization

Apparent thermal conductivity λ (W/(mK)) was measured using a heat flow meter (HFM) apparatus in accordance with the governing standard EN 12667 [10]. Prior to measurement in the HFM, the specimens were conditioned at 10 ºC and 50 % relative humidity (RH) for a minimum of 12 h. Four specimens with dimensions 600 mm x 600 mm were measured for each of the aerogel insulation blankets. The size of the gap containing the specimen was registered by sensors in the HFM apparatus. The thermal conductivity of AB1 was determined with the gap size set to the nominal thickness of the aerogel blanket, whereas for AB2 and AB3 the gap size was set according to measured specimen thickness because the nominal thickness was not reported by the manufacturer. The effect of uniaxial compression on thermal conductivity was measured for AB1 and AB2 by compressing the aerogel blankets in the HFM apparatus in steps of 0.2 mm, and extracting thermal conductivity data after steady-state was achieved.

In order to relate the uniaxial compression to applied compressive stress, stress-strain curves for AB1 and AB2 were recorded in accordance with EN 826. [11] The specimen dimensions were 10 mm x 10 mm.

The effect of relative humidity on thermal conductivity and heat capacity was studied by bringing two specimens of AB2 in equilibrium with atmospheres with different RH, and measuring the thermal conductivity using a Hot Disk Thermal Constants Analyzer (Model TPS 2500S) employing a disk-type Kapton sensor with a 14.61 mm radius placed between the samples. The instrument and method has previously been explained thoroughly by Ihara et al. [8]. Calibration with stainless steel reference samples was performed prior to measurements. The aerogel blanket specimens were dried at 70 ºC for 72 hours and cooled in a sealed container holding silica gel desiccant. They were subsequently exposed to increasingly higher RH, using a selection of saturated salt solutions. The temperature and RH of the chamber were monitored. The temperature was approximately 22 ºC during all measurements. The specimen holder and sensor were mounted inside the sealed container. The specimens were not removed from the specimen holder between measurements in order to measure at the exact same location, i.e. to make the humidity level the only changing parameter. A minimum of 6 measurements were conducted at each humidity level, with a time interval of 90 min. In order to estimate the moisture content of the aerogel specimens, identical specimens were stored in the container, and periodically weighed.

3. Results and discussion

The apparent thermal conductivity values at initially measured thickness are presented in Table 2. According to EN 12667 [10], the minimum specimen thickness should be 30 mm in order to keep uncertainty in the specimen height measured by the instrument to an acceptable level. The thicknesses of the studied aerogel blankets were all below 30 mm. The minimum thickness value may be exceeded by stacking specimens; however, this introduces another source of uncertainty due to discontinuity and contact resistance at the interfaces between specimens. The apparent thermal conductivity and corresponding uncertainty (standard error of the mean) were compared for single and stacked specimens. A one-sided t-test of variance showed that the difference in average thermal conductivity of specimens measured in stacks versus individually does not exceed 5 %, within a confidence interval of 90 %. Furthermore, the average thermal conductivity measured on stacked specimens is well within one standard error of the mean of the values measured on individual specimens. Thus, we assume that the difference in measured thermal conductivity obtained with single or stacked specimens is not significantly larger than the variation between specimens.

Table 2. Parameters and results from measurements of apparent thermal conductivity of aerogel insulation blankets.

Aerogel blanket	Total insulation thickness (mm)	Number of stacked specimens	Number of measurements	Total number of specimens	Average thermal conductivity (10^{-3} W/(mK))	Standard error of the mean (10^{-3})
AB1	10	1	4	4	17.6	0.46
AB1	40	4	4	16	17.5	0.091
AB2	17.9 (average)	1	4	4	17.0	0.28
AB2	35.1 (average)	2	4	8	16.9	0.29
AB3	10.4 (average)	1	4	4	18.1	0.075

The effect of uniaxial compression on thermal conductivity was studied using individual specimens because errors associated with interfacial effects are presumably dependent on the applied pressure. The apparent thermal conductivity as a function of percentage compressive strain and density is plotted in Figure 1a and b, respectively, for four individual specimens of AB1 and AB2. Regardless of initial λ-value, the apparent thermal conductivity steadily decreased with increasing density/strain in the start with a slope of approximately $-6\cdot10^{-5}$ $Wm^2/(kgK)$. The thermal conductivity vs. density curve for thermal insulation materials typically displays a minimum, after which the thermal conductivity increases upon further density increase [12]. It is possible that such a minimum would also be found for the aerogel blanket materials if the density could be further increased, however, the curves showed no indication of flattening out at the pressures obtained in the HFM. The thickness of AB1 and AB2 were reduced up to 18 % and 13 %, respectively, corresponding to applied pressures of approximately 34 and 32 kPa according to the stress strain curve in Figure 2 a.

When evaluating the effect of uniaxial compression on thermal insulation properties, it is important to be aware that the thermal resistance also decreased upon uniaxial compression. Due to space restrictions, the plot of thermal resistance vs. uniaxial compression is not shown here. The thermal resistance decreased 3 to 5 % at compressive strain of 10 % for both AB1 and AB2, analogous to the best values reported by Hoseini et al. [7]. Thus, it is possible to increase the thermal resistance within a defined volume by compressing aerogel blankets into a confined space, nevertheless, the thermal resistance per mass aerogel insulation will decrease. In terms of applied pressure, aerogel insulation blankets have appreciably better thermal insulation properties under uniaxial compression than e.g. fibreglass batts. However, one could argue that this mostly reflects the higher compressive strength of the aerogel blankets. In terms of percentage strain, the properties are more comparable, e.g. Graves and Yarbrough [13] reported 5.5 to 8.5 % reduction in thermal resistance at a compressive strain of 10 % for a selection of fibreglass batts.

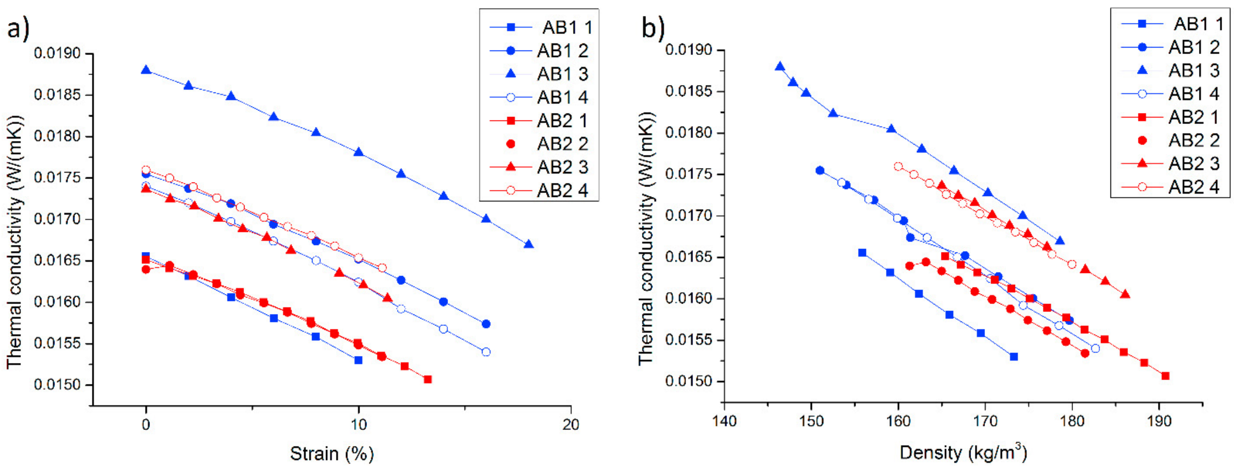

Figure 1. Apparent thermal conductivity of aerogel insulation blankets AB1 (4 specimens) and AB2 (4 specimens) as a function of (a) percentage strain and (b) density.

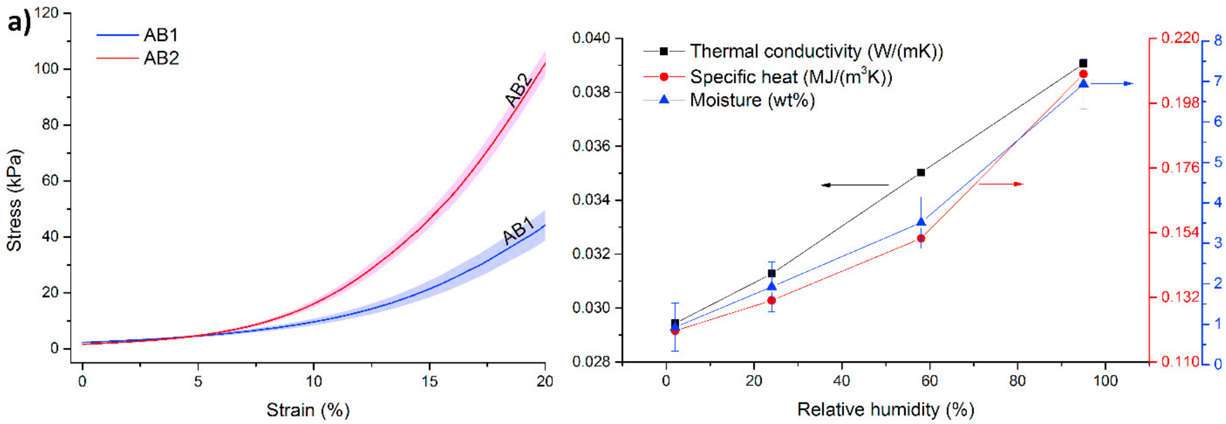

Figure 2. (a) Stress-strain correlation for aerogel insulation blankets AB1 and AB2. The solid lines represent the average of 5 measurements, and standard error of the mean is indicated by the shaded areas. (b) Correlation of thermal conductivity, specific heat and moisture content for aerogel insulation blanket AB2. The standard error of the mean for moisture content is indicated with error bars.

Both thermal conductivity and specific heat increased with increasing relative humidity of the surroundings, and the data correlated well with the specimen weight gain as shown in Figure 2 b. At 95 % RH, the moisture uptake of the aerogel insulation specimens was 7 wt%, with a corresponding increase in thermal conductivity of 32 %. A one-way factorial analysis of variance showed that the increase in thermal conductivity was statistically significant at a significance level of 1 %. Notice that the absolute values of the thermal conductivity measured by the Hot Disk divides substantially from the values measured by the HFM. We speculate that the thermal properties at the surface of the aerogel blankets may be considerably different from those in the bulk. Hence, these measurements should only be viewed as an indication that the aerogel blankets absorb moisture to some extent, and that the moisture levels do indeed affect thermal conductivity. Furthermore, the wt% moisture uptake and increase in thermal conductivity of the aerogel insulation blankets was comparable to that reported by Lakatos [9]. Lakatos measured up to 40 % increase in the thermal conductivity at 90 % RH using an HFM. The larger increase observed by Lakatos may be due to individual differences between the aerogel blanket specimens. Given the insignificant effect of humidity on the thermal conductivity of aerogel granules [8], it is plausible that the glass/polymer fibres of the aerogel blanket are responsible for the majority of the thermal conductivity increase. However, this should be investigated further in order to improve moisture tolerance of the aerogel insulation blankets.

Another important aspect when considering the feasibility of integrated aerogel solutions is environmental impact. Schlanbusch et al. have compared LCA cradle-to-gate global warming potential [kg CO_2 eq] and total primary energy use [MJ] for several thermal insulation materials using a functional unit equivalent to 1 m^2 insulation material with a thickness resulting in a thermal resistance of R = 1 m^{2}K/W [14]. The highest values were reported for vacuum insulation panels (~9 kg CO_2 eq, ~180 MJ), whereas mineral wool products had the lowest values (~1 kg CO_2 eq, ~19 MJ). Aerogel insulation materials were not included in the comparison by Schlanbusch et al. [14]. However, cradle-to-gate values extracted from the environmental product declaration of Aspen Spaceloft white/grey [15] and converted to the functional unit of 1 m^2 insulation material giving R = 1 m^{2}K/W show a global warming potential of 19 kg CO_2 eq and total primary energy consumption of 189 MJ. Thus, from an environmental perspective other insulation materials may be a better choice in applications where space restriction is not of essence.

4. Conclusions

The effect of uniaxial compression and humidity on the thermal conductivity of commercially available aerogel insulation blankets were measured in order to assess the feasibility of integrating aerogel blankets into other products, exemplified by window frames or masonry blocks. The apparent thermal conductivity was shown to decrease with increasing uniaxial compression/density. Up to 11.5 % decrease in apparent thermal conductivity was obtained at a compressive strain of 16 %, corresponding to an applied stress of approximately 22 kPa. Thus, in applications where the surrounding material is able to sustain a compressive stress on the aerogel insulation, it is possible to achieve lower thermal transmittance (U) values by packing more aerogel insulation material into a restricted space. Overall, the thermal insulation properties of the aerogel insulation blankets remained excellent within the range of compressive stress investigated in this study (up to about 40 kPa), making aerogel integration highly interesting for building components that may be used under compression. However, the effect of moisture on the thermal conductivity may be a concern. A 32 % increase in thermal conductivity was observed upon exposure to an atmosphere of 95 % relative humidity (RH). Exposure to water in the condensed form would presumably have an even greater impact on thermal conductivity. Thus, in order to widen the range of applications for fibre reinforced aerogel insulation materials, further investigations should be conducted to understand and improve their hygrothermal properties. In applications where the insulation material is protected from moisture, and the space for insulation is highly restricted, aerogel integration could be highly advantageous. However, due to high global warming potential and energy use associated with the current aerogel production, other insulation materials may be a better choice in applications where space restriction is not of essence.

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References

[1] Schiavoni S, D'Alessandro F, Bianchi F, Asdrubali F. Insulation Materials for the Building Sector: A Review and Comparative Analysis. Renew Sust Energ Rev. 2016;62:988-1011.
[2] Cuce E, Cuce PM, Wood CJ, Riffat SB. Toward Aerogel Based Thermal Superinsulation in Buildings: A Comprehensive Review. *Renew Sust Energ Rev.* 2014;34:273-99.
[3] Koebel MM, Huber L, Zhao S, Malfait WJ. Breakthroughs in Cost-Effective, Scalable Production of Superinsulating, Ambient-Dried Silica Aerogel and Silica-Biopolymer Hybrid Aerogels: From Laboratory to Pilot Scale. *J. Sol-Gel Sci. Technol.* 2016;79(2):308-18.
[4] Van Den Bossche N, Buffel L, Janssens A. Thermal Optimization of Window Frames. *Energy Procedia*. 2015;78:2500-5.
[5] Gustavsen A, Grynning S, Arasteh D, Jelle BP, Goudey H. Key Elements of and Material Performance Targets for Highly Insulating Window Frames. *Energy and Build.* 2011;43(10):2583-94.
[6] Bardy ER, Mollendorf JC, Pendergast DR. Thermal Conductivity and Compressive Strain of Aerogel Insulation Blankets under Applied Hydrostatic Pressure. *J Heat Transfer.* 2006;129(2):232-5.
[7] Hoseini A, Malekian A, Bahrami M. Deformation and Thermal Resistance Study of Aerogel Blanket Insulation Material under Uniaxial Compression. *Energy and Build.* 2016;130:228-37.
[8] Ihara T, Jelle BP, Gao T, Gustavsen A. Aerogel Granule Aging Driven by Moisture and Solar Radiation. *Energy and Build.* 2015;103:238-48.
[9] Lakatos Á. Investigation of the Moisture Induced Degradation of the Thermal Properties of Aerogel Blankets: Measurements, Calculations, Simulations. *Energy and Build.* 2017;139:506-16.
[10] European Committee for Standardization. 2001 EN 12667 Thermal Performance of Building Materials and Products - Determination of Thermal Resistance by Means of Guarded Hot Plate and Heat Flow Meter Methods - Products of High and Medium Thermal Resistance
[11] European Commitee for Standardization. 2013 EN 826 Thermal Insulating Products for Building Applications - Determination of Compression Behaviour.
[12] Byggforskserien 573.344 Varmeisolasjonsmaterialer. Typer og Egenskaper. (Thermal insulation materials. Classes and properties.) SINTEF Building and Infrastructure 2004
[13] Graves RS, Yarbrough DW. The Effect of Compression on the Material R-Value of Fiberglass Batt Insulation. *J Build Phys*. 1992;15(3):248-60.
[14] Schlanbusch RD, Fufa SM, Sørnes K, Kristjansdottir T. Energi- og Klimagassanalyse av isolasjonsmaterialer. (Energy and Climate Gas Analysis of Insulation Materials.) SINTEF akademisk forlag 2014.
[15] Aspen Aerogels Inc. S-P-00725 Environmental Product Declaration of Spaceloft Aerogel Insulation 2015.