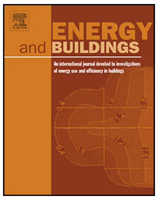
Energy and Buildings 152 (2017) 472–482

Contents lists available at ScienceDirect

Energy and Buildings

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



Aerogel-based materials for building applications: Influence of granule size on thermal and acoustic performance

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ARTICLE INFO

Article history:
Received 24 February 2017
Received in revised form 12 June 2017
Accepted 25 July 2017
Available online 28 July 2017

Keywords:
Silica aerogel
Thermal conductivity
Acoustic properties
Transmission loss (TL)
Absorption coefficient (α)
Aerogel-based materials

ABSTRACT

Aerogel was one of the most promising nano-materials for use in buildings and its thermal performance was widely discussed in the literature while an accurate study of acoustic properties was never provided. The aim of the paper is to investigate experimentally the influence of granules size on both thermal and acoustic properties of granular aerogels and aerogel-based solutions (a plaster and a translucent polycarbonate panel) for energy saving in buildings. Several kinds of aerogels were investigated, ranging from small granules (0.01–1.2 mm) to large granules (1–4 mm). For each kind of aerogel, the absorption coefficient (α) and Transmission Loss (TL) were measured at normal incidence in a traditional impedance tube, taking into account 5 thicknesses (15, 20, 25, 30 e 40 mm) and thermal conductivity (λ) was evaluated by the Heat Flux Meter, setting up an appropriate methodology because of the sample nature. The aerogel granules outperformed the conventional insulating materials: depending on the particle sizes, λ varies in 19–23 × 10(ˆ-3) W/(mK) range at 10 °C. The smallest granules (highest density) had the best performance, both in terms of thermal and acoustic insulation: α-values and TL better than the ones of rock wool were achieved (α = 0.95 and TL = 15 dB at about 1700 Hz). The good acoustic behaviour was confirmed also considering the two aerogel-based solutions for buildings: the peak of the absorption coefficient of the aerogel-based plaster was 0.29 at about 1050 Hz, compared to a value of about 0.1 of conventional plasters; simultaneously, λ diminished from 0.7 W/mK to 0.05 W/mK.

1. Introduction

In the background of superinsulation materials, aerogels are achieving a more and more important role, especially in the granular form. It is less expensive than the monolithic aerogel; furthermore the difficulty in producing monoliths without defects, cracks, and inhomogeneity can compromise the optical quality of the transparent layer [1]. Granular aerogels are easier to handle, because they could be poured like a powder [1], but their optical and thermal performance is in general worse than the monolithic ones [2,3], due to the air trapped in the inter-granular macropores, even if the granules themselves offer the same thermal conductivity as the monoliths. For this reason, research on monolithic silica aerogel for fenestration applications recently started again and new technics for their preparation were proposed, by means of a rapid supercritical extraction process implemented in an industrial hot press [4].

In the last decade the attention of the researchers was focused on the characterization of granular aerogels [2,3,5–17], but a systematic investigation of the influence of the granule size was concentrated only in some of the last studies [18–20].

Aerogels are nanostructured solid materials characterized by low density and high porosity (> 90%); they can be defined as superinsulation materials, due to their low thermal conductivity. Koebel et Al. [1] in 2012 introduced a definition of superinsulation materials basing on the value of the thermal conductivity instead of the total heat transfer coefficient U-value: the limit for superinsulation materials is set at a value of λ of 0.020 W/mK and aerogels can be considered in this class of materials. The low values of the thermal conductivity of aerogels are due to the combination of low density and small pores, which contribute to reduce heat transfer. Density of SiO_2 aerogels vary in the 80–200 kg/m^3 and in general the thermal conductivity increases when density increases, due to the conduction through the silica network and the radiation and gaseous conduction through the air inside the pores. But at the same time the small pores limit conductive and convective gas transport, therefore it contributes to reduce the thermal conductivity, overcoming the effect of the increased density. Thermal conductivity

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http://dx.doi.org/10.1016/j.enbuild.2017.07.071
0378-7788/

can in fact be reduced also by compression of the granular aerogel bed, which reduces the volume fraction of air in the inter-granular macroporosity [1,21].

Thermal conductivity of aerogels is in general declared in the 0.012–0.020 W/mK range [1,8,13], but in some cases it can reach a value of 0.008 W/mK [7]. When compared to other insulation and superinsulation materials, aerogels show excellent fire resistance, effect as vapour barrier, resistance to direct sunlight, durability, and sound absorption [13].

Neugebauer et al. [14] describe a technique for compacting a bed of granular aerogel P100 (Cabot Corporation) in order to reduce the thermal conductivity. The particle size distribution is measured by means of a tower of sieves agitated by a motorized sieve shaker. The density of the initial naturally settled bed was about 68 kg/m^3 and the thermal conductivity $24 \times 10\hat{(}-3)$ W/(mK). Different degrees of compression were applied and the corresponding thermal conductivity was measured. Results showed that as the compression (and the density) increases, the thermal conductivity decreases, reaching a minimum value of about $13 \times 10\hat{(}-3)$ W/(mK) at a bed density of about 150–165 kg/m^3 (or a compressive strain between 55 and 59%).

The optical properties of both granular and monolithic aerogel were studied since many years [7,2,3]. The solar and visible transmission of monolithic silica aerogels is in general higher than the granular one, while the U-values are comparable in non evacuated conditions. The difference in the optical properties depends on the parameters of the sol-gel process, especially for the monolithic panes, and on the granule size for the granular form, but the influence of the granule size was not highlighted in the these studies. Furthermore the monolithic pane allows the view through it, but it scatters the transmitted light resulting in a hazy picture and modified colour rendering: the light reflected appears in fact bluish, while the transmitted one is slightly reddened. Granular aerogel, on the contrary, does not allow the view through it, resulting in a completely diffuse transmission able to avoid glare.

Less studies are available on the acoustic properties of aerogels [22–25]. In a first study in 1998 [22] the acoustic propagation in aerogels and alcogels was investigated, while the acoustic reflection coefficient, the attenuation, and the sound velocity were studied in [23] and were compared with those of a glass wool sample. Small and large granule aerogels were considered and it was found that the glass wool exhibits better absorption properties than large granule aerogels, while small granules have a higher attenuation than glass wool. Furthermore it was demonstrated that the best behaviour of aerogel granules as audible sound absorbers was found when used in coupled layers with different granule sizes. It is confirmed in [24], where the attenuation of three layer absorbers was investigated in an impedance tube: the first two layers act as an impedance matcher, while the third one acts as an absorber. Three samples of granular aerogels of 1 mm, 3 mm, and 80 μm diameters were arranged in different orders and thicknesses; the results could be related to the transmission loss, even if data inside the impedance tube is overestimated. A maximum attenuation of about 60 dB was obtained for a sample constituted by three layers 2 cm thick of decreasing diameter (3 mm, 1 mm, and 80 μm). Granular aerogels with very low granule size (powders) were also used to simulate the snow behaviour, in order to use the acoustic emissions to predict avalanches [25].

In the recent years (2014–2016) a systematic investigation of the influence of the granule size on the optical, thermal, and acoustic performance of aerogels was carried out [18–20]. Gao et al. [18] used silica aerogels granules of 3–5 mm and prepared aerogel granules with smaller particle sizes by grinding and sieving the received granules. Three glazing units were assembled with two clear glass panels (thickness 4 mm each) and an intermediate gap (thickness 14 mm), filled respectively with air, large granules, and small granules, for a total thickness of the glazing units of 22 mm. The thermal and optical properties were investigated and the results showed that they are strongly correlated to the particle size. The glazing unit with small granules showed lower U-values with respect to the one with large granules (1.05 W/m^{2}K instead of 1.19 W/m^{2}K), but also lower visible light transmittance and solar factor ($\tau_v = 0.15$ and g = 0.27 for small granules; $\tau_v = 0.50$ and g = 0.57 for large granules). The same values for the glazing unit with air in the gap were U = 2.86 W/m^{2}K, $\tau_v = 0.81$, and g = 0.75, therefore the systems with small and large granules allowed improved thermal insulation performance having a reduction in heat losses of about 63% and 58% respectively. Ihara et al. [15] investigated the thermal properties of glazing systems assembled with two types of aerogel granules. Small granules (diameter 0.7–1.2 mm) and large granules (diameter 1.2–4.0 mm) were used, in order to verify the tendency (highlighted in other studies [26]) of the granules of different size to produce some sort of line pattern (as clouds), due to their biased distribution. Nevertheless in this study it was not observed and the appearance of the tested samples was quite uniform. The samples were assembled with 6-mm-thick heat strengthened glasses, with 30 and 60 mm gap thickness filled with aerogel granules. The U-values were measured by means of hot box tests with various tilt angles, in order to evaluate the influence of the convection on the thermal performance. Results showed that convection in the granular cavity does not affect the U-values, which are approximately the same (within the measurement uncertainty) for vertical and horizontal position of the glazing system. The center-of-glass U values were about 0.52 and 0.28 W/m^{2}K respectively for the samples with 30 and 60 mm thick granular cavities, resulting in a calculated thermal conductivity of the granular layer of about 17–19 W/mK. The influence of the granule size was investigated only in terms of moisture permeance and results showed no significant difference.

Sachithanadam and Joshi [19] investigated the effect of granule size on the acoustic properties of silica aerogel composites; the absorption coefficient and the transmission loss were measured by the impedance tube method both for different thick layers of granules (10 and 15 mm) and protein-based silica aerogel composites. Silica aerogel granule sizes varied in the 0.50–3.35 mm range, distributed into six groups of nominal size. Results showed that for the granule layers the absorption coefficient tends to decrease with the increase in granule size and with the increase in layer thickness; the smaller granules tend to be more compact, therefore the higher silica content contributes to the tortuous path of the sound waves to propagate through the nano-pores of the granules. A further investigation on layers of 5 cm thickness was carried out in order to find the peak value of the absorption coefficient; it was equal to 0.86 for the sample with the granules diameter in the 1.00–1.40 mm range and to 0.81 for the one with the granules diameter in the 1.40–2.00 mm range, both at 980 Hz. The same samples showed also the best values of the average transmission loss, equal to 14.8 and 15.4 dB respectively.

In the last year the Authors started a systematic study on the influence of the granule size on the thermal and acoustic properties of aerogels. In a preliminary step thermal conductivity and transmission loss of three granule sizes were investigated [20]: large (0.7–4.0 mm), medium (0.7–2.0 mm), and small (0.01–1.2 mm) granues, with densities of 65–70, 70–75, and 80–85 kg/m^3 respectively. Results showed that the small granules have the best performance both in terms of thermal and acoustic properties. Depending on the granule size, the thermal conductivity varies in the $19–22 \times 10\hat{(}-3)$ W/(mK) range at 10 °C, while a Transmission Loss value of 13 and 19 dB at 6400 Hz were obtained for small granule layers 20 and 40 mm thick respectively. The maximum values of the Transmission Loss of medium and large granules are in the 10–14 dB range.