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Transparent insulating materials for buildings energy saving: experimental results and performance evaluation

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Abstract

The reduction of energy consumption for heating and air conditioning and electric energy saving in illumination plants could be improved by innovative Transparent Insulating Materials (TIMs), which aim to optimize two opposite requirements: transparency and thermal insulation. Aerogel is one of the more promising for use in highly energy-efficient windows: in addition to the low thermal conductivity (0.010 W/(m K) in evacuated conditions), a high solar energy and daylight transmittance is achieved. Eight samples were manufactured, by assembling several types of glass with monolithic and granular aerogel in the interspace. Measurements of transmission and reflection properties were carried out and the energetic and luminous parameters (light transmittance (τ_v), solar factor (g) and thermal transmittance (U)) were calculated. U-values slightly higher than 1 W/m^2K were obtained for all the samples. The monolithic aerogel introduces a better light transmittance (τ_v = 0.60) than granular one (τ_v = 0.27), while U-values are comparable in not evacuated conditions. In order to evaluate the aerogel employing in buildings, a prototype of an aluminium frame window with granular aerogel in interspace was realized. Thermal and acoustic properties of the prototype were evaluated according to the standards. The thermal transmittance of the innovative glazing system was little lower than 1 $W/(m^2 K)$ and it showed also good acoustic properties: the R_w index was 3 dB higher than the one of a conventional window with air in interspace.

Keywords

Advanced building materials, TIMs (Transparent Insulation Materials), Aerogel, Thermal Transmittance.

Introduction

The recent directives of the European Parliament on the buildings energy performance make energy saving one of the most relevant aims in residential and not residential buildings (offices, public buildings, etc.). Buildings account in fact for 40 % of Europe's energy use and one third of its greenhouse gas emissions.

Windows have a double role in the thermal envelope: their low thermal insulation performance, for which they have to be as small as possible in order to reduce energy consumption for heating and air conditioning, and natural lighting, for which they have to be as large as possible for visual comfort and electric energy saving in illumination plants. Windows have to assure also adequate acoustic insulation level [1]. These contrasting requirements could be overcome using particular materials with both characteristics of high thermal insulation and high lighting transmittance: transparent insulation materials (TIMs).

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Among TIMs, aerogel is a very interesting material for use in highly energy-efficient windows: in addition to the low thermal conductivity of silica aerogel, a high solar energy and daylight transmittance is achieved. In fact, by using the passive solar energy through windows, it is possible to reduce the annual energy consumption for space-heating in cold climates, such as in the northern European Countries or in highlands [2].

Aerogel is a highly porous light material with a number of exceptional and even unique physical properties: it attracts the attention of researchers in various areas of science and technology. The first aerogel specimens appeared eighty years ago [3]. The production is localized in Europe (Sweden, Germany), USA, Japan and Russia. Aerogels are manufactured on the basis of silicon dioxide (SiO_2, amorphous quartz): they are constituted by approximately 96% of air and 4% open-pored structure of silica; such structure confers the characteristic of extreme lightness to the material (density is about 50-200 kg/m^3). Aerogel has the capacity to absorb IR radiation and has the lowest thermal conductivity among solid materials (approximately it is equal to 0.021 W/(m K) at room temperature, lower than one of air). The optical and thermal properties of aerogel depend on both the starting silica source and the condition of its preparation process [4-6].

Several are the fields of application of aerogel [7]:

- microelectronics, because aerogels are the materials with the lowest dielectric constant and their use reduces the parasitic capacitances and thus increases the response speed;
- electrical engineering: the use of carbon silica aerogel as electrodes with an extremely large area allows the creation of superhigh capacitances;
- acoustics: aerogel is interesting for acoustic devices because the sound propagation velocity in it is rather low;
- oil and gas pipelines: insulation with aerogel provides many advantages for oil and gas transport operators;
- space exploration: aerogel is used as thermal insulator in USA spacecraft; furthermore, for in space investigations carried out on artificial satellites, systems with aerogel are studied in order to capture microparticles (micrometeorites, microscopic fragments of comets and asteroids);
- heat insulation of buildings: aerogel is a transparent material with interesting optical properties, such as high light and solar transmittance but, differently from the normally used transparent materials such as glass, it has also very good thermal insulation properties; it is in fact used as transparent wall in solar collectors and in office buildings.

Aerogel is available as panes and as granules [8-9]. Glazing systems with monolithic aerogel are not yet used in mass production [10-11], but during the year 2005 many types of translucent granular aerogel appeared on the market for daylighting systems [12-13]. The different systems found in the Literature (polycarbonate panels, structural panels, insulated glasses) are able to offer excellent thermal performance, high quality of the diffused light, a good solar heat gain and good sound insulation characteristics [14].

In this context, in the present paper innovative glazing systems with aerogel in the interspace were investigated. The optical and thermal properties of the proposed glazing systems were measured, in order to evaluate buildings energy saving. The optical properties of the single pane of monolithic aerogel were firstly measured, evaluating spectral transmittance vs. wavelength. Then, eight different samples were made, by assembling several kinds of glasses in various combinations, with monolithic and granular aerogel. Moreover three samples with granular aerogel manufactured by the European companies leaders in the daylighting were considered.

Transmission and reflection coefficients vs. wavelength were measured by the spectrophotometer UV/VIS/NIS SolidSpec 3700; results were employed to calculate the energetic and luminous parameters and the performance of the different samples were compared.

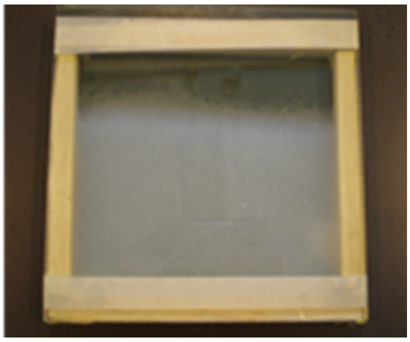
In order to evaluate the aerogel employing in buildings, a prototype of an aluminium frame window with granular aerogel in interspace was realized; thermal and acoustic properties of the prototype were evaluated according to the standards.
Finally the improvements in thermal performance of the innovative glazing systems, compared to "conventional" windows, were estimated.

2. Highly insulation windows with aerogel: samples description

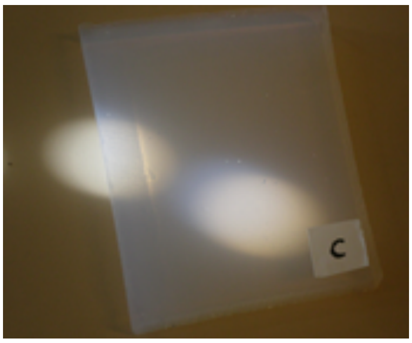
In this work both kinds of silica aerogel were analysed: monolithic silica aerogel, thickness 14 mm (samples dimension: 90x90x14 mm) [15], and granular aerogel characterized by grain sizes comprised between 0.5 mm and 3.5 mm [16].
Four samples were realized by assembling, in various combinations, a pane of aerogel with several kinds of glasses: float glass (4 mm), low-e coated glass and acoustic laminated glasses, which consists of two glass panes with one special acoustic PVB (polyvinyl butyral) interlayer to reduce incident sound energy; the glasses are:

- 6/7 a: laminated glass with two glass panes of 3 mm thickness and PVB layer (0.76 mm);
- 6/7 low-e: laminated glass with low-e coat;
- 10/11 a: laminated glass with two glass panes of 5 mm thickness and PVB layer (0.76 mm).

Granular aerogel were also incorporated into glazing systems with the same glasses layers; the interspace was filled with aerogel grains of 14 mm thickness (four samples).
Moreover three samples manufactured by two European companies operating in daylighting systems were considered [17, 18]. The glazing system *okagel* [17] consists of two glass layers filled with granular aerogel. It can be used in roof lights as well as in façade elements; the translucent material in the gap enables optimal uniform lighting in the room and exceptionally good thermal insulation up to 0.3 W/(m^2 K). Finally, two nanogel-filled rooflight solutions *(Xtralite)* in polycarbonate [18] were considered (two different thicknesses, 16 and 25 mm).
The samples characteristics (external and internal slab, interspace and total thickness) are reported in table 1. Some photos of the eleven samples are shown in figure 1.

a)

b)

The samples assembled with monolithic (a) and granular aerogel (b)



Monolithic aerogel sample | Okagel | Xtralight

Figure 1: The tested samples with monolithic and granular aerogel in interspace

Table 1: Main characteristics of the samples

N.	Sample	External slab and thickness	Interspace and thickness	Inner slab and thickness	Total thicknes s (mm)
1	**4 - aer - 4**	float, 4 mm	monolithic, 14 mm	float, 4 mm	22
2	**4 - aer -6/7a**	float, 4 mm	monolithic, 14 mm	acoustic, 6/7 mm	24
3	**4 - aer- 6/7 low-e**	float, 4 mm	monolithic, 14 mm	low-e, 6/7 mm	24
4	**10/11a - aer -6/7a**	acoustic, 10/11 mm	monolithic, 14 mm	acoustic, 6/7 mm	30
5	**4 - gran - 4**	float, 4 mm	granular, 14 mm	float, 4 mm	22
6	**4 – gran - 6/7a**	float, 4 mm	granular, 14 mm	acoustic, 6/7 mm	24
7	**4 – gran - 6/7 low-e**	float, 4 mm	granular, 14 mm	low-e, 6/7 mm	24
8	**10/11a – gran - 6/7a**	acoustic, 10/11 mm	granular, 14 mm	acoustic, 6/7 mm	30
9	**Okagel**	float, 4 mm	granular, 25 mm	float, 4 mm	33
10	**Xtralite 16**	polycarbonate, 1mm	granular, 14 mm	polycarbonate, 1mm	16
11	**Xtralite 25**	polycarbonate, 1mm	granular, 23 mm	polycarbonate, 1mm	25

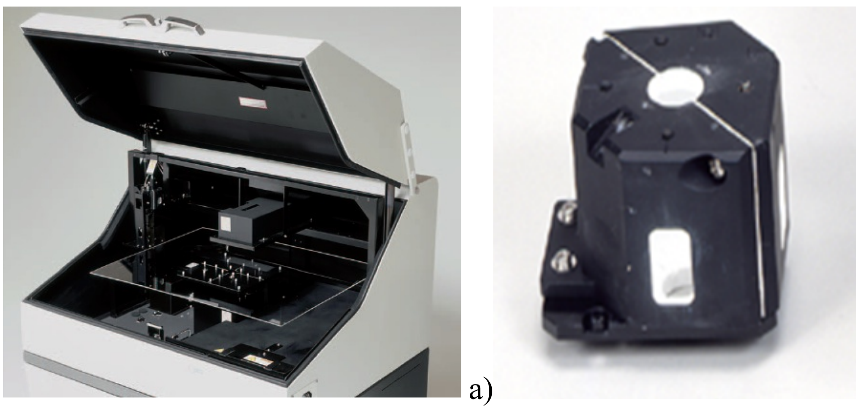
3. Evaluation of samples optical properties

3.1 Experimental facility and methodology

Measurements were carried out by a spectrophotometer UV/VIS/NIS SolidSpec 3700 [19], available at the Thermotechnical Laboratory of the Department of Industrial Engineering, University of Perugia. Thanks to a large sample compartment (900x700x350 mm), it allows to evaluate spectral transmittance and reflectance of large window samples by keeping them horizontal (Figure 2.a).

The instrument can work in the wavelength range 165-3300 nm and it is equipped with three detectors: a photomultiplier tube (PMT) detector for the ultraviolet and visible region; InGaAs and PbS detectors makes a significantly high sensitivity in the near-infrared region. The spectrophotometer is equipped with an integrating sphere (Figure 2.b) that is able to determine the spectral reflectance and the spectral transmittance of scattering materials.

The spectral transmittance $\tau(\lambda)$ and the spectral reflection $\rho(\lambda)$ were measured in the wavelength range 300 - 2500 nm; because of the material inhomogeneity, each measurement was repeated five times by changing the sample position; the final result was given by the mean of the obtained values.



a) b)

Figure 2: The spectrophotometer UV/VIS/NIS SolidSpec 3700 with its sample compartment (a) and the integrating sphere (b)

3.2 Experimental data

At the beginning, measurements of transmission coefficient vs. wavelength of pane aerogel were carried out (Figure 3).

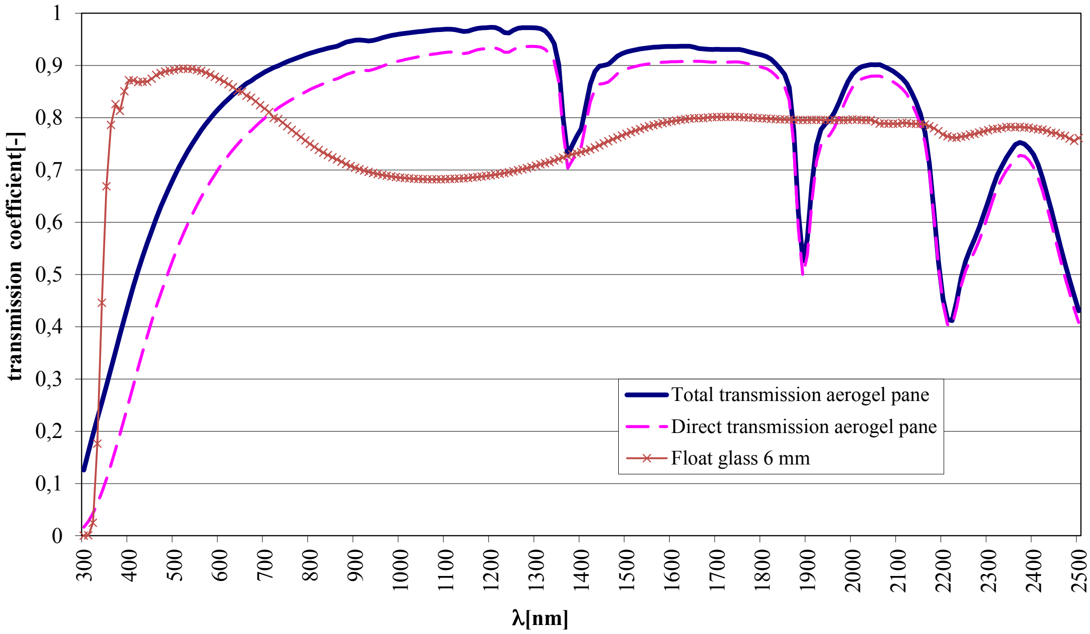


Figure 3: Total and only direct transmission coefficient vs. wavelength of monolithic aerogel pane

Aerogel has high transmittance for radiation in the solar spectrum as well as in the visible part of the spectrum, similar to a conventional clear glass of 6 mm thickness. The comparison with direct transmission and total light transmission measurements (with this method all the light that passes through the sample was measured, consisting of the directly transmitted light and the diffusely transmitted light) showed that part of the radiation is diffused when transmitted through the material, due to structural inhomogeneities. The scattered radiation gives objects a hazy look when observed through the aerogel: the material displays a slight bluish haze when an illuminated piece is viewed against a dark background and slightly reddens transmitted light. Moreover, peaks of selective absorption are shown ($\lambda \cong 1400$ nm, $\lambda \cong 1900$ nm and $\lambda \cong 2200$ nm) in the spectral transmission values [20, 21].

Figures 4 and 5 show transmission coefficient values (obtained by total light transmission measurements) for all the samples.

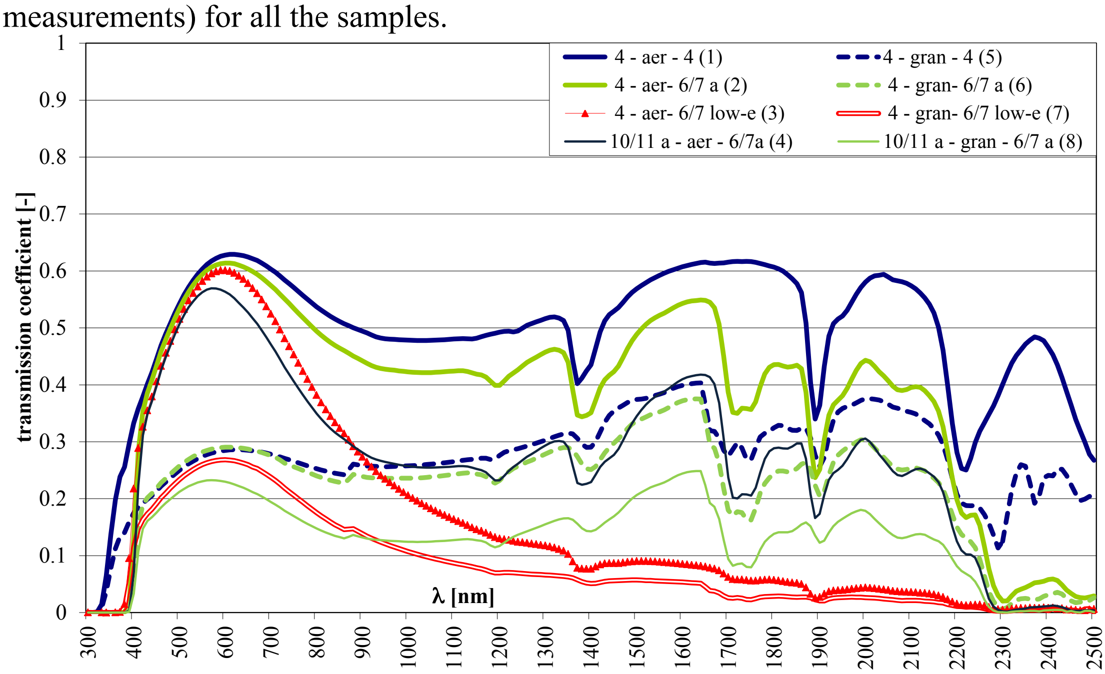


Figure 4: Transmission coefficient of assembled samples

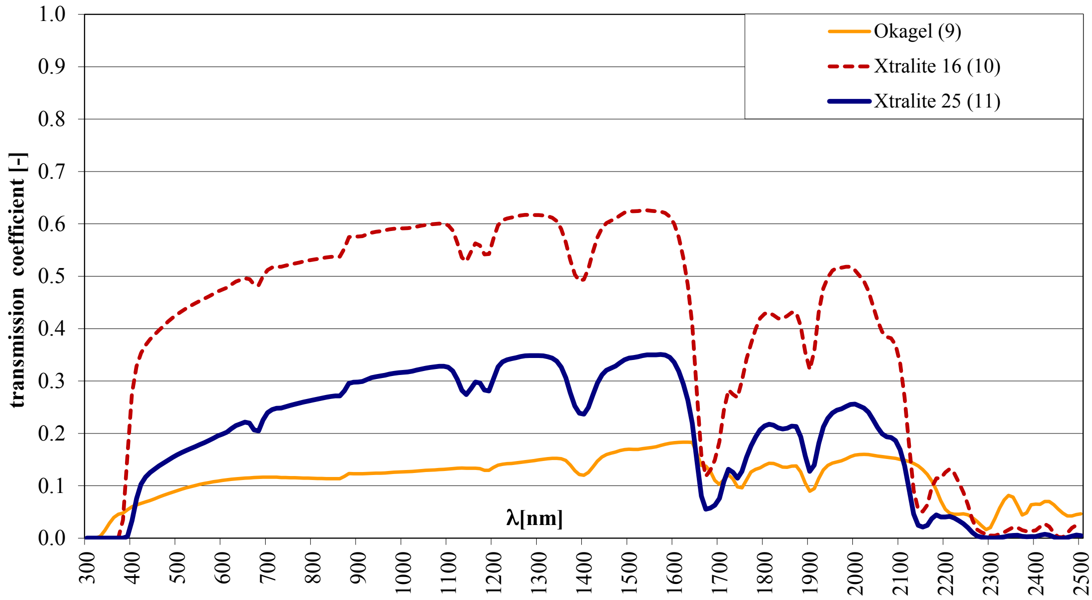


Figure 5: Transmission coefficient of Okagel and Xtralite

Data about the assembled samples show similar trends for the samples assembled with float and acoustic glass, but the transmission coefficient for monolithic aerogel is higher than the one of granular sample; in the visible range the sample (1) with float glass layers and monolithic aerogel is about 0.6; for the same external and internal glasses but with granular aerogel it diminishes up to 0.3 (5). Finally, samples 4 - aer- 6/7 low-e (3) and 4-gran- 6/7 low-e (7) show a different trend in the IR range, due to the low-e coated glass.

Xtralite glazing systems show a 50% reduction in transmission when the thickness of granular aerogel increases from 16 to 25 mm. The transmission of the Okagel sample is low and in the visible range it is about 0.1.

Results about reflection coefficients were not reported, for sake of brevity; they were employed for determining the absorption coefficient of the samples.

3.3 Optical and energetic parameters calculation

Optical characteristics were calculated in compliance with UNI EN 410/2000 [22]: light transmittance τ_v and reflectance ρ_v (wavelength range 380-780 nm), solar direct transmittance τ_e, reflectance ρ_e and absorbance α_e (wavelength 780-2500) for all the samples are reported in table 2.

Table 2: Optical parameters calculated for the samples

N.	Sample	τ_v	ρ_v	τ_e	ρ_e	α_e
1	4 - aer - 4	0.60	0.13	0.51	0.11	0.38
2	4 - aer -6/7a	0.58	0.13	0.46	0.10	0.44
3	4 - aer- 6/7 low-e	0.57	0.13	0.35	0.14	0.51
4	10/11a - aer -6/7a	0.55	0.11	0.37	0.08	0.55
5	4 - gran - 4	0.27	0.14	0.26	0.12	0.62
6	4 – gran - 6/7a	0.28	0.13	0.24	0.10	0.66
7	4 – gran - 6/7 low-e	0.25	0.13	0.16	0.13	0.71
8	10/11a – gran - 6/7a	0.22	0.11	0.16	0.08	0.76
9	Okagel	0.10	0.13	0.11	0.11	0.78
10	Xtralite 16	0.45	0.16	0.46	0.15	0.39
11	Xtralite 25	0.18	0.17	0.21	0.14	0.65

In order to compare the performance of the samples with different fillings, three important parameters were considered: τ_v, g and U-values. The light transmittance τ_v represents the glazing system capacity to diffuse the natural light indoors: it is important since the natural light concurs to save electric energy in the daytime and affects general health of human beings. g and U, instead, determine the quantity of the heat transfer through the glazing systems and affect the calculation of heating and cooling loads.
According to the European standard [22], the total solar energy transmittance g is the sum of the solar direct transmittance τ_e and the secondary heat transfer factor (q_i) of the glazing towards the inside:

$$g = \tau_e + q_i$$

where q_i depends on the heat transfer by convection and the solar direct absorbance α_e of the samples. Only for the assembled samples, the solar factor g was calculated from the measurement results in compliance with UNI EN 410; the sample with monolithic aerogel in interspace was considered as an evacuated triple glazing. The U value was calculated in compliance with the method described in the technical norm UNI ISO 673 [23], depending on the internal and external heat transfer factors, the thermal conductivity values and thickness of the glass layers and material in interspace. The U-values are referred to the centre of glazing, excluding the frame and dividers effects; for the thermal conductivity a value of 0.010 W/(m K) was assigned to monolithic aerogel, corresponding to evacuated aerogel glazing at a pressure of 10 hPa [13, 15], while for granular aerogel a value of 0.018 W/(m K) was considered [16].
In order to evaluate the performance improvement due to the innovative glazing systems, a comparison with "conventional" windows characterized by the same inner and external slab (float glass 4 mm) was carried out. Literature data were used for windows normally used in Italy and in the UE countries, in order to accomplish the law limits [24] . Results are shown in figure 6.

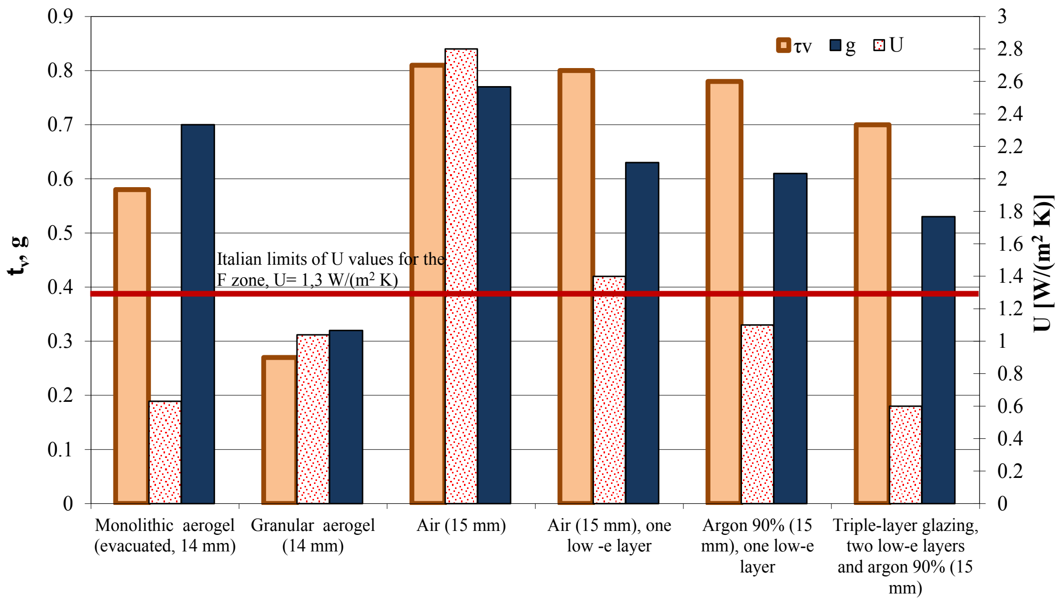


Figure 6: Comparison between the performance of samples characterized by the same inner and external slab (float glass 4 mm) and conventional windows

The evacuated glazing systems with monolithic aerogel allow to obtain a calculated U-value little higher than 0.6 W/(m^2 K), while the light transmittance is equal to 0.58 and the calculated solar factor is 0.70; data are in good agreement with experimental values obtained in a previous work [13]. For the granular aerogel glazing unit, a calculated U-value little higher than 1 W/(m^2

K) and a calculated solar factor equal to 0.32 were obtained, but the light transmittance is lower than 0.30.

With respect to conventional glazing systems, the innovative windows reduce visible transmittance of about 28% for the monolithic aerogel samples and of 33% for the capillary TIM samples; the reduction is equal to 66% for the samples with granular aerogel in interspace. Furthermore, introducing monolithic aerogel in the same thickness interspace instead of air, the thermal transmittance decreases from 2.7 W/(m^2 K) to 0.6 W/(m^2 K).

The most recent European [24] and Italian Laws [25] suggest more and more strict limits for thermal transmittance values. Starting by the year 2011, the U values for the F zone (the coldest zone in Italy) will be lower than 1.3 W/(m^2 K): this goal could be obtained just by using double glazing with argon gas in the interspace (air space thickness = 15 mm) coupled with low–e coated glasses (surface emissivity < 0.1), which have a U–value of 1.1 W/(m^2 K). If the thermal transmittance should be further reduced until 0.6 W/(m^2 K), a triple-layer glazing with two low-e layers and argon (90%) filled must be considered. However, the light transmission and the solar factor are reduced because of the double low-e layer and the weight of the window increases by 1/3.

4. Window with granular aerogel: Prototype production and experimental evaluation of the performance

In order to evaluate the aerogel employing in buildings, a prototype of an aluminium frame window with granular aerogel was realized. This sample has a double-glazing unit with aerogel in interspace. Aerogel in granular form was put in a gap 15 mm depth; indoor and outdoor layers are float glasses of 4 mm thickness (Figure 7). This sample is an aluminium frame with two mobile shutters (thickness 58 mm) and double rabbet; the thickness of the frame is about 51 mm.

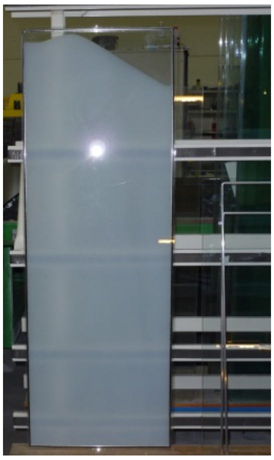


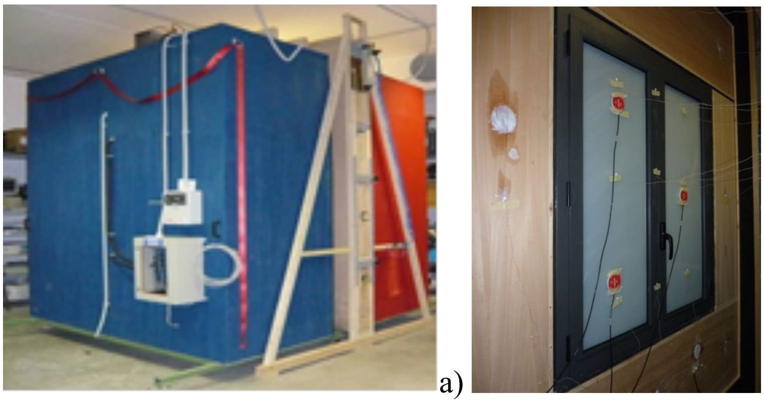
Figure 7: Setting-up of the aerogel glazing system

To compare innovative and conventional solutions, in the same frame a double-glazing unit of 23 mm thickness with an air gap of 15 mm depth and a laminated glass with low-e coat (4 mm) was installed; both the samples have external dimensions 1175 x1454 mm.

In order to validate the theoretical values, thermal trasmittance was measured, thanks to the calibrated hot box apparatus available at the Department of Industrial Engineering of the University of Perugia, according to UNI EN ISO 12567-1 [26].

The instrument apparatus is the calibrated hot-box (Figure 8.a); it is composed of two chambers (dimensions 2.5 m x 1.2 m x 3.2 m height). The outer walls of the hot chamber are made with very thick insulation (24 cm of foam polystyrene), to minimise conduction losses, and the power flow through the walls is measured for a range of hot chamber and laboratory temperatures, using the calibration panels. The thermal transmittance of the specimen is

obtained from the heat rate needed to maintain the hot chamber at a fixed temperature, once the temperature of the cold chamber is fixed and steady-state conditions are achieved. The cold side is cooled by a chiller placed completely outside the cold chamber. In order to avoid direct radiation effects, in both the chambers a panel with known emissivity properties is placed between the probes and the heat sources. In order to assure a convective equilibrium, two ventilation systems are placed in both the chambers. The hot box needs a series of calibration measurements, in order to evaluate the heat losses different from the flux transmitted through the specimen, such as heat transfer through the surround panel and all flanking losses [27].
Moreover, three thermofluximeters are fixed on the glass and on the window frame (Figure 8.b).
Experimental results of the measured parameters and the computed values are shown in table 3.



a) b)

Figure 8: View of the hot box apparatus and of the sample during the laboratory test

Table 3: Experimental results: parameters measured for the conventional window and for the glazing prototype with aerogel in interspace

	Conventional window	**Glazing prototype with aerogel**
Measured parameters		
Mean temperature of the hot side (°C)	19.44	19.19
Power of the hot side (W)	99.26	80.57
Mean temperature of the cold side (°C)	-1.51	-0.78
Mean value of the heat flow (thermofluximeter method)	26.95	18.04
Calculated values		
Heat flow through the sample [W/m^2]	40.59	30.50
Temperature gap between the hot side and the cold one	20.43	19.52
Global thermal trasmittance (Hot box method)[1][W/(m^2 K)]	2.20	1.69
Normalized thermal trasmittance of the glazing evaluated by thermofluximeter method[1] [W/(m^2 K)]	1.46	0.99

[1] Normalized considering air surface thermal resistance equal to 0.17 (m^2 K)/W.

Thanks to the granular aerogel incorporated into the glazing system, the thermal transmittance of the window is reduced by 23%, from 2.20 W/(m^2 K) to 1.69 W/(m^2 K); the innovative glazing system contribution is remarkable: in fact, thermal trasmittance, evaluated by thermofluximeter method, is about 1.46 W/(m^2 K) for the conventional glazing with laminated glass with low-e coat; the thermal trasmittance of aerogel glazing system is lower than 1 W/(m^2 K) and it agrees with the estimated value.
Finally, in order to evaluate the acoustic performance of the window prototype in terms of sound insulation in the buildings façades, the sound insulation index R according to UNI EN ISO 140-3 [28] was measured and the weighted sound insulation index R_w according to UNI

EN ISO 717-1 [29] was calculated. The experimental campaign was carried out at the Laboratory of Acoustics of the University of Perugia, where two coupled reverberating rooms are available, wholly in compliance to UNI-EN ISO 140-1 [30].
Sound reduction index (R) vs. frequency for the windows is reported in figure 9. With the same aluminium frame, the granular aerogel in interspace increases the sound reduction index values in all the frequency range (100-500 Hz), above all in the central range (500 - 2000 Hz).
Finally, for the innovative prototype the R_w value (R_w= 37 dB) was 3 dB higher than the one of conventional windows with air in interspace (R_w= 34 dB), confirming good acoustic insulation properties.

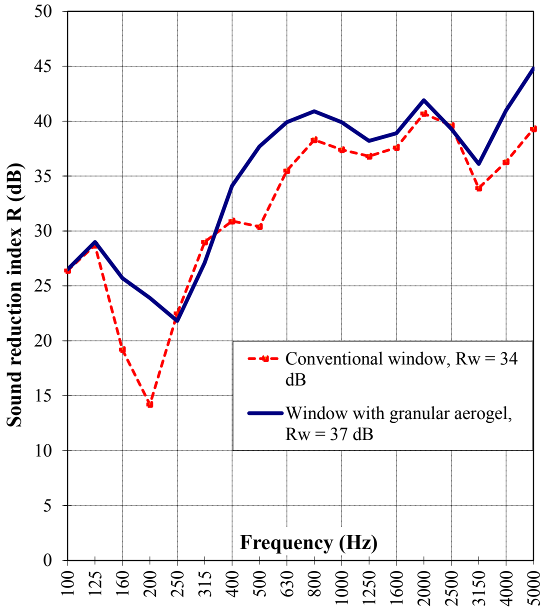


Figure 9: Sound reduction index (R) values vs. frequency for the conventional window and for the glazing prototype with aerogel in interspace

Conclusions

In the recent years there has been a growing interest in high insulation glazing systems, because of their important role in building envelope from thermal, acoustic and visual point of view. Among innovative transparent materials, aerogel is one of the more promising because of very low thermal conductivity and transparency.
In order to evaluate the performance of this new material, some samples with monolithic and granular aerogel were investigated, thanks to optical parameters measurements carried out by the UV/VIS/NIS spectrophotometer SolidSpec 3700. The better performance was given by monolithic aerogel, both for light transmittance (0.58 in interspace between two 4 mm float glasses) and thermal insulation (U = 0.63 W/(m^2 K), calculated in evacuated conditions); moreover the solar factor is 0.70. For the granular systems, a U-value little higher than 1 W/(m^2 K) was obtained, but the light transmittance is little lower than 0.3. With respect to a conventional window (double glazing with a low-e layer) in keeping with Law limits [25 - 26], 55% reduction in heat losses is achieved by monolithic aerogel, with only a 27% reduction in light transmittance; for the granular systems, the reduction was about 25% in heat losses, but 66% in light transmission.
The estimated results were confirmed by the experimental campaign on the aluminium window prototype with granular aerogel in interspace. The thermal transmittance measured by means of the calibrated hot box apparatus was little lower than 1 W/(m^2 K) for the innovative glazing system; thanks to granular aerogel, the aluminium frame window prototype showed a 23% reduction in thermal transmittance with respect to the same window with air in interspace and a

low-e glass layer. Moreover, the granular aerogel in interspace can improve sound insulation of the building envelope: the acoustic measurements on the sample showed that the weighted sound insulation index R_w for the aerogel window prototype was 3 dB higher than the same window with air in interspace.
Glazing systems with aerogel are very interesting for employing in buildings, above all in monolithic panes, especially considering very strict limits imposed by the law or in highly glazed buildings; nevertheless, the research is seeking to solve some problems such as the phenomenon of light scattering, which gives a reduced optical quality of vision through the material; furthermore, the production process is very complex and it does not allow the use of very large sheets, without altering performance. Finally, the costs reduction should allow a distribution on wide scale.

Nomenclature

g: Total solar energy transmittance or solar factor [-]
R: Sound Reduction Index [dB]
R_w: Weighted Sound Reduction Index [dB]
U: Thermal transmittance [W/(m^2 K)]
λ: Wavelength [nm]
α_e: Solar absorbance [-]
ρ_e: Solar reflectance [-]
ρ_v: Light or visible reflectance [-]
τ_e: Solar direct transmittance [-]
τ_v: Light or visible transmittance [-]

References

[1] Oral G.K., Yener A.K., Bayazit N.T., 2004, "Building envelope design with the objective to ensure thermal, visual and acoustic comfort conditions", *Building and Environment*; Vol 39, No 3, pp. 281–287.
[2] AbuBakr Bahaj S., James P.A.B., Jentsch M.F., 2008, "Potential of emerging glazing technologies for highly glazed buildings in hot arid climates", *Energy and Buildings*, Vol 40, No 5, pp. 720–731.
[3] Kistler S.S., "Coherent Expanded Aerogels and Jellies", *Nature*, Vol 127, pp. 741-741.
[4] Tajiri K., Igarashi K., 1998, "The effect of the preparation conditions on the optical properties of transparent silica aerogels", *Solar Energy Materials & Solar Cells*, Vol 54, pp. 189-195.
[5] Anderson A.M., Wattley C.W., Carroll M.K., 2009, "Silica aerogels prepared via rapid supercritical extraction: Effect of process variables on aerogel properties", *Journal of Non-Crystalline Solids*, Vol. 355, No 2, pp. 101-108.
[6] Reim M., Reichenauer G., Körner W., Manara J., Arduini-Schuster M., Korder S., Beck A., Fricke J., 2004, "Silica-aerogel granulate – Structural, optical and thermal properties", *Journal of Non- Crystalline Solids*, Vol 350, pp. 358-363.
[7] Akimov Y.K., 2003, Fields of Application of Aerogels (Review), *Instrument and Experimental Technologies*, Vol 3, pp. 287-299.
[8] Schultz J.M., Jensen K.I., Kristiansen F.H., 2005, "Super insulating aerogel glazing": *Solar Energy Materials & Solar Cells*, Vol 89, pp. 275-285.
[9] Reim M., Beck A., Körner W., Petricevic R., Glora M., Weth M., Schliermann T., Schmidt, Pötter F.J., Fricke J., 2002, "Highly insulating aerogel glazing for solar energy usage", *Solar Energy*, Vol 1, pp. 21–29.
[10] Duer K., Svendsen S., 1998, "Monolithic Silica Aerogel in Superinsulating Glazings"; *Solar Energy*, Vol 63, pp. 259-267.

[11] Jensen K.I., Schultz J.M., Kristiansen F.H., 2004, "Development of windows based on highly insulating aerogel glazings" *Journal of Non- Crystalline Solids*, Vol 350, pp. 351–357.
[12] Rigaccia A., Einarsrudb M., Nilsenb E., Pirardc R., Ehrburger-Dolled F., Chevalier B., 2004, "Improvement of the silica aerogel strengthening process for scaling-up monolithic tile production" *Journal of Non- Crystalline Solids*, Vol 350, pp. 196-201.
[13] Schultz J.M., Jensen K.I., 2008, "Evacuated aerogel glazings", *Vacuum;* Vol 82, pp. 723–729.
[14] Reim M., Korner W., Manara J., Korder S., Arduini-Schuster M., Ebert H.P., Fricke J., 2005, "Silica aerogel granulate material for thermal insulation and daylighting*", Solar Energy*, Vol 2, pp. 131-139.
[15] Airglass AB, Sweden, web site: http://www.airglass.se/
[16] Cabot Corporation, USA, web site: http://w1.cabot-corp.com/index.jsp
[17] Okalux GmbH, Germany, web site: http://www.okalux.com/
[18] Xtralite Rooflight, web site: http://www.xtralite.co.uk/
[19] Shimadzu, 2008, UV/VIS Spectrophotometer, Training course for analysis of solid samples.
[20] Buratti C., 2003, "Transparent insulating materials: experimental data and buildings energy saving evaluation", Proceedings of ENERGY & ENVIRONMENT 2003, First International Conference on Sustainable Energy, Planning & technology in Relationship to the Environment, Halkidiki, Greece.
[21] Buratti C., Moretti E., 2007, "Misura delle proprietà energetiche e luminose di sistemi vetrati con aerogel granulare", Proceedings of the Convegno annuale ATI, Salerno, Italy, 2007 (in italian).
[22] UNI EN 410, 2000, "Vetro per Edilizia - Determinazione delle Caratteristiche Luminose e Solari delle Vetrate" (in italian).
[23] UNI EN 673, 2005, "Vetro per edilizia - Determinazione della trasmittanza termica - Metodo di calcolo" (in italian).
[24] AGC Flat Glass Europe, Brussels, 2009.
[25] EC, 2002, "Directive 2002/91/EC of the European Parliament and of the Council of 16 December 2002 on the energy performance of buildings".
[26] Italian Legislative Decree 59/09 "Regolamento di attuazione dell'articolo 4, comma 1, lettere a) e b), del decreto legislativo 19 agosto 2005, n. 192, concernente attuazione della direttiva 2002/91/CE sul rendimento energetico in edilizia"(in italian).
[27] EN ISO 12567-1, 2000, "Thermal performance of windows and doors - Determination of thermal transmittance by hot box method - Complete windows and doors".
[28] Asdrubali F., Baldinelli G., Bianchi F., Libbra A., Muscio A., 2010, "Comparative analysis of different methods to evaluate the thermal conductivity of homogenous materials", Proceedings of ASME - ATI - UIT Thermal and Environmental Issues in Energy System, May 16-19, 2010, Sorrento, Italy.
[29] UNI EN ISO 140-3, 2006, "Acustica. Misurazione dell'isolamento acustico in edifici e di elementi di edificio – Parte 3: Misurazione in laboratorio dell'isolamento acustico per via aerea di elementi di edificio"(in italian).
[30] UNI EN ISO 717-1, 2007, "Acustica. Valutazione dell'isolamento acustico in edifici e di elementi di edificio. Isolamento acustico per via aerea"(in italian).
[31] UNI EN ISO 140-1, 2006, "Acustica. Misurazione dell'isolamento acustico in edifici e di elementi di edificio – Parte 1: Requisiti per le attrezzature di laboratorio con soppressione della trasmissione laterale"(in italian).

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