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Lighting and Energetic Characteristics of Transparent Insulating Materials: Experimental Data and Calculation

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Key Words

Aerogel · Capillary TIM · Light transmittance · Solar factor · Thermal transmittance · Transparent insulation materials

Abstract

This paper reports the study of thermal and optical properties of innovative transparent insulating materials (TIM) for glazing systems: silica aerogel (pane and granular) and capillary geometric media. Twenty-one samples were assembled with several kinds of glasses in various combinations with TIM. Transmission and reflection coefficients versus wavelength were measured and the results were elaborated in compliance with UNI EN 410/2000. The better performance was given by the monolithic aerogel both for light transmittance (0.58 in interspace between two 4 mm float glasses) and thermal insulation ($U = 0.63\,W \cdot m^{-2} \cdot K^{-1}$). The solar factor was 0.70. The performance of the innovative glazing systems was compared with data related to windows normally used in Italy and in EU countries, in order to comply with the limits of the local normative standard required for thermal transmittance. The results showed a very promising behaviour of TIMs, in fact a 60% reduction in heat losses with respect to a double glazing with a low-e layer was achieved, with only a 27% reduction in light transmittance. For the granular systems, a U-value little higher than $1\,W \cdot m^{-2} \cdot K^{-1}$ with the same total thickness was obtained, even if the light reduction was about 66%.

Nomenclature

g = total solar energy transmittance or solar factor
U = thermal transmittance ($W{\cdot}m^{-2}{\cdot}K^{-1}$)
λ = wavelength (nm)
ρ_e = solar reflectance
ρ_v = light or visible reflectance
τ_e = solar direct transmittance
τ_v = light or visible transmittance

Introduction

The lack of the conventional energy sources and the recent target of the Kyoto Protocol has made energy

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saving as one of the most important aims in buildings [1]. Transparent window openings have in fact 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 transmittance of natural lighting, for which they have to be as large as possible for visual comfort and saving electrical energy in illumination plants [2]. These contrasting requirements could be overcome using particular materials with both characteristics of high thermal insulation and high lighting transmittance, such as the transparent insulation materials (TIMs) [3].

The innovative translucent materials as aerogel are very appropriate for use in highly energy-efficient windows. In addition to the low thermal conductivity of silica aerogel ($0.010\,W \cdot m^{-1} \cdot K^{-1}$ in evacuated conditions), a high solar energy and daylight transmittance have been achieved. In fact, using the passive solar energy through windows, the annual energy consumption could be reduced for space-heating in cold climates, such as in the northern European Union (EU) Countries or in highlands. Alternatively, TIMs can be constituted by transparent cellular array (honeycomb) placed in the air layer, to limit the convection heat losses in the air gap, without substantially modifying the daylighting and solar performance [4].

In this context, in this paper, three innovative glazing systems were investigated, realised by two glasses of different kinds and thicknesses and with TIM in the interspace:

– windows with an aerogel pane in interspace;
– windows with granular aerogel in interspace;
– windows with capillary TIM in interspace.

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 first measured, evaluating spectral transmittance versus wavelength. The measurements were carried out in a spectrophotometer using the standard method and with the integrating sphere, in order to evaluate the material scattering. Then, 17 different samples were made, by assembling several kinds of glasses in various combinations, with monolithic and granular aerogel. Capillary layers of TIM were also inserted between the two glass plates and other four samples were considered. A total of 21 samples were obtained.

Transmission and reflection coefficients versus wavelength were measured. The results were employed to calculate the energetic and luminous parameters and the performance of the different samples was compared.

Finally, the improvements in thermal performance of the innovative glazing systems were estimated by comparison with the "conventional" windows, considered as a window normally used in Italy and in the EU countries in order to comply with the limits of the local normative standard on thermal transmittance. It was assumed as "conventional" a window with a thermal transmittance of $1.6\,W \cdot m^{-2} \cdot K^{-1}$ (flat glass 4 mm – air interspace 12 mm – low-e glass 4 mm).

Materials: Transparent Insulating Materials

Some innovative transparent solutions concerning TIM were considered: silica aerogel and capillary TIM.

Aerogel is a highly porous light material with a number of exceptional and even unique physical properties. This material has attracted the attention of researchers in various areas of science and technology. The first aerogel specimens appeared 80 years ago [5]. The production of the TIM material is localised in Europe (Sweden, Germany), USA, Japan and Russia. Aerogels are manufactured on the basis of silicon dioxide (SiO_2, amorphous quartz), constituted by approximately 96% of air and 4% open-pored structure of silica. Such structure would confer the characteristic of extreme lightness to the material (density $\approx$50–200 $kg \cdot m^{-3}$). Aerogel has the capacity to absorb IR radiation and has the lowest thermal conductivity among solid materials ($\approx 0.021\,W \cdot m^{-1} \cdot K^{-1}$ at room temperature, lower than the thermal conductivity of air). The optical and thermal properties of aerogel would depend on both the starting silica source and the condition of its preparation process [6–8].

The fields of application of aerogel are numerous [9]:

– microelectronics, because aerogels are the materials with the lowest dielectric constant and the use of such a material would reduce the parasitic capacitances and thus increase the response speed;
– electrical engineering: the use of carbon silica aerogel as electrodes with an extremely large area would allow the creation of super high capacitances;
– acoustics: aerogel is appropriate for acoustic devices because of the low sound propagation velocity;
– oil and gas pipelines: insulation with aerogel would provide many advantages for oil and gas transport operators;

- space exploration: aerogel has been 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 good optical properties, such as high light and solar transmittance, but behave differently to the normally used transparent materials such as glass. It has also very good thermal insulation properties, and could be used as transparent wall in solar collectors and in office buildings [10–12].

Aerogel may be available as panes and as granules. Glazing systems with monolithic aerogel have not yet been used in mass production [13,14], but during the year 2005 many types of translucent granular aerogel have appeared on the market for daylighting systems [15,16]. The different systems found in the literature (polycarbonate panels, structural panels, insulated glasses) are reported to provide excellent thermal performance, high quality of the diffused light, a good solar heat gain and good sound insulation characteristics [17,18].

The other investigated solution, the capillary TIM, uses polymeric geometric structures in order to limit thermal dispersions of a double glazing [4,19]. Honeycomb transparent insulation has been applied in building insulation, in skylights, as well as in solar collectors. The capillaries would prevent heat transmission in the inner cavity, not only with respect to convection (the honeycomb cell size is normally small enough to eliminate any convective heat transfer), but also in terms of heat radiation. When inserted in a double glazing, a good improvement of the thermal insulation could be achieved, even if high thickness is necessary (between 50 and 500 mm). Moreover, the capillary slab would diffuse direct sunlight and create an illumination of the room with daylight. Direct solar radiation into the room and thus hard shadows could be prevented.

Materials: Characteristics of the Samples

In this work, both kinds (aerogel and capillary TIM) of TIM were used. Four samples of the monolithic silica aerogel, thickness 14 mm, were supplied by Airglass AB, Sweden [20]; the granular aerogel was supplied by Cabot Corporation, USA, (Nanogel®) [21]; the grain sizes were between 0.5 and 3.5 mm.

The geometric media considered in this study was a polycarbonate square section capillary TIM, with a diameter of 2 mm and a total thickness of the layer of 50 mm. The material was supplied by the OKALUX Kapillarglas Gmbh and is called Okalux [22].

A total of 21 samples were obtained, by assembling the three kinds of TIM in the interspace of different glasses, all supplied by Saint-Gobain (Italy) [23] (Figure 1).

Six samples were realised by assembling, in various combinations, a pane of aerogel with several kinds of glasses: float glasses of various thicknesses, reflecting glasses and low-e coated glasses.

Granular aerogel was also incorporated into glazing systems with two glass layers of different types; the interspace of 8, 10 and 15 mm (10 samples) was filled with aerogel in interspace. Moreover, a sample constituted by a structure in polycarbonate with granular aerogel in interspace (PC-gr8-PC) was considered, to carry out a comparison with data from the producer [21].

Four samples were realised by inserting capillary layers of TIM between the two glass plates.

In the samples with capillary TIM and granular aerogel, glasses with light reflecting characteristics ($\rho_v = 0.32$; $\rho_e = 0.26$; $\tau_v = 0.37$; $\tau_e = 0.29$) were not considered as external slabs, since they are not suitable for daylighting purposes.

The characteristics of all the samples (external and internal slab, interspace and total thickness) are reported in Table 1.

Experimental Facility and Methodology

Measurements were carried out by a spectrophotometer Cary 2300, available at the Thermotechnical Laboratory of the Department of Industrial Engineering, University of Perugia. The spectral transmittance of a sample was evaluated as the ratio of the intensity of the monochromatic radiation measured by the two detectors, one measuring the radiation through the sample and the other measuring the direct radiation. The integrating sphere is a particular accessory used to determine the spectral reflectance and the spectral transmittance of scattering materials (Figure 2), within the wavelength range 185–3152 nm. The characteristics of the spectrophotometer have been described in the previous papers [24,25]. Measurements were carried out by dividing the interval of the wavelengths in two parts: 300–800 and 800–2000 nm. Each measurement was repeated three times and

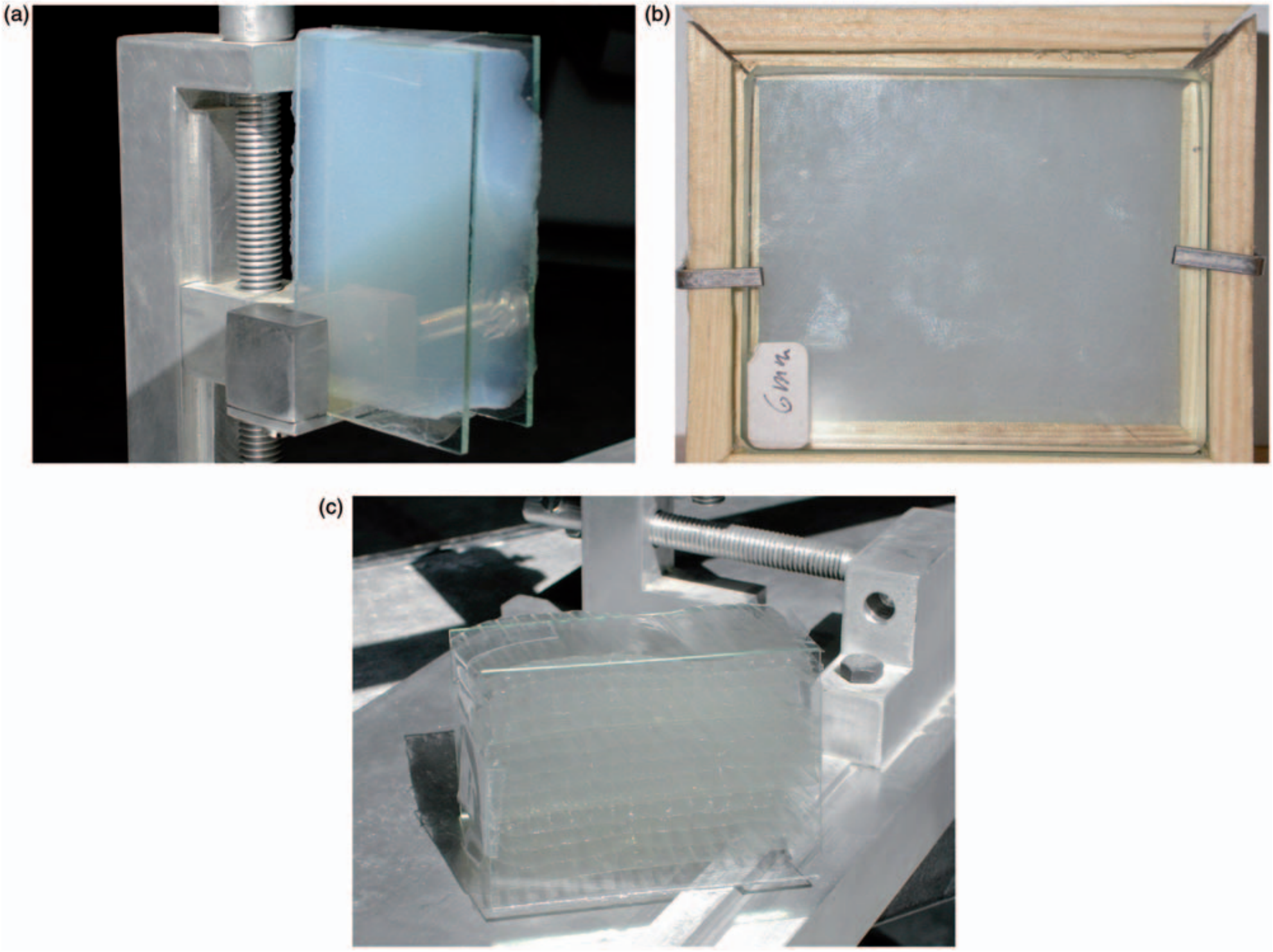

Fig. 1. Double glazing with monolithic aerogel (a), granular aerogel (b) and capillary TIM (c) in the interspace.

the final result was given by the mean values in each wavelength interval.

In order to evaluate the performance of the samples, light transmittance, τ_v, (wavelength range 380–780 nm) and solar direct transmittance, τ_e, (wavelength 780–2500) were calculated, in compliance with UNI EN 410/2000 [26]. Reflection measurements of the same samples were carried out with the integrating sphere; as the spectral transmittance, the light reflectance, ρ_v, and the solar direct reflectance, ρ_e, were also calculated.

Experimental Results and Discussion

In order to evaluate the transmission characteristics of pane aerogel, measurements of transmission coefficient versus wavelength were carried out, both in the standard configuration and with the integrating sphere. The results are shown in Figure 3.

Aerogel has a high transmittance for radiation in the solar spectrum as well as in the visible part of the spectrum. Values are similar to the ones of a conventional clear glass of 6 mm thickness. The transmission coefficients measured without the integrating sphere (standard method) were compared with the data of the integrating sphere. They showed that part of the radiation is diffused when transmitted through the material, due to structural inhomogeneities. In fact, if the material is diffusive, the probe would not be able to detect all the transmitted radiation if this is scattered out of its area while, if the integrating sphere was inserted, the scattered radiation would be captured, giving a more reliable value of the transmittance of the sample.

Scattering could give the object a hazy look when observed through the aerogel. The material would display

Table 1. Samples with TIM in the interspace

Sample	External slab and thickness	Interspace and thickness	Inner slab and thickness	Total thickness (mm)
F4-aer-F4	Float glass, 4 mm		Float glass, 4 mm	22
F5-aer-F5	Float glass, 5 mm		Float glass, 5 mm	24
F6-aer-F6	Float glass, 6 mm		Float glass, 6 mm	26
F5-aer-LE4	Float glass, 5 mm	Aerogel pane, 14 mm	Low-e coated glass Eko plus, 4 mm	24
R6-aer-F5	Reflecting glass Antelio Steel Grey, 6 mm		Float glass, 5 mm	25
R6-aer-LE4	Reflecting glass Antelio Steel Grey, 6 mm		Low-e coated glass Eko plus, 4 mm	24
PC-gr8-PC	Polycarbonate, 1 mm	Granular aerogel, 8 mm	Polycarbonate, 1 mm	10
F5-gr10-LE4	Float glass, 5 mm	Granular aerogel, 10 mm	Low-e coated glass Eko plus, 4 mm	19
F4-gr8-F4	Float glass, 4 mm	Granular aerogel, 8 mm	Float glass, 4 mm	16
F4-gr10-F4	Float glass, 4 mm	Granular aerogel, 10 mm	Float glass, 4 mm	18
F4-gr15-F4	Float glass, 4 mm	Granular aerogel, 15 mm	Float glass, 4 mm	23
F5-gr8-F5	Float glass, 5 mm	Granular aerogel, 8 mm	Float glass, 5 mm	18
F5-gr10-F5	Float glass, 5 mm	Granular aerogel, 10 mm	Float glass, 5 mm	20
F5-gr15-F5	Float glass, 5 mm	Granular aerogel, 15 mm	Float glass, 5 mm	25
F6-gr8-F6	Float glass, 6 mm	Granular aerogel, 8 mm	Float glass, 6 mm	20
F6-gr10-F6	Float glass, 6 mm	Granular aerogel, 10 mm	Float glass, 6 mm	22
F6-gr15-F6	Float glass, 6 mm	Granular aerogel, 15 mm	Float glass, 6 mm	27
F4-tim-F4	Float glass, 4 mm		Float glass, 4 mm	58
F5-tim-F5	Float glass, 5 mm		Float glass, 5 mm	60
F6-tim-F6	Float glass, 6 mm	Capillary TIM, 50 mm	Float glass, 6 mm	62
F5-tim-LE4	Float glass, 5 mm		Low-e coated glass Eko plus, 4 mm	59

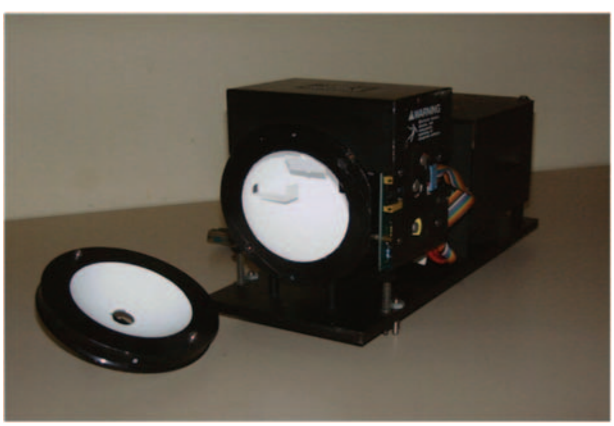

Fig. 2. The integrating sphere.

a slight bluish haze when an illuminated piece is viewed against a dark background and would emit slightly redden transmitted light [25,27]. A selective absorption was shown ($\lambda \cong 1350$ and $\lambda \cong 1900$ nm) in the spectral transmission values, due to inhomogeneities of the material structure originated during the production process.

The transmission and reflection coefficient measurements of the 21 samples were then performed. All the measurements were carried out with the integrating sphere, since tests on aerogel showed it is a light scattering material, both in pane and granular form, due to the characteristics of the material. The capillary TIMs have a diffusive behaviour too, but this is due to their high thickness with respect to the samples dimensions. Figure 4 shows the results for samples with pane aerogel in interspace. The data illustrate the same trend for the samples characterised by similar glasses with different thicknesses (F4-aer-F4; F5-aer-F5; F6-aer-F6) and the transmission coefficient would be diminished when the thickness of the glasses increases. The measurement of the sample F5-aer-LE4 showed a different trend for wavelengths higher than 800 nm. It was due to the low-e coated glass in the inner position. Finally, the transmission coefficient values measured were shown to be lower in the samples R6-aer-F5 and R6-aer-LE4 above all in visible range, because of the reflecting glasses (reflection coefficient $\rho_v = 0.32$) [23].

In Figure 5, the sample PC-gr8-PC was representative of granular aerogel behaviour; a selective absorption at $\lambda \approx 1400$ nm, $\lambda \approx 1650$ nm and, such as pane aerogel, $\lambda \approx 1900$ nm was found. In order to evaluate the influence of the interspace thickness in granular aerogel samples,

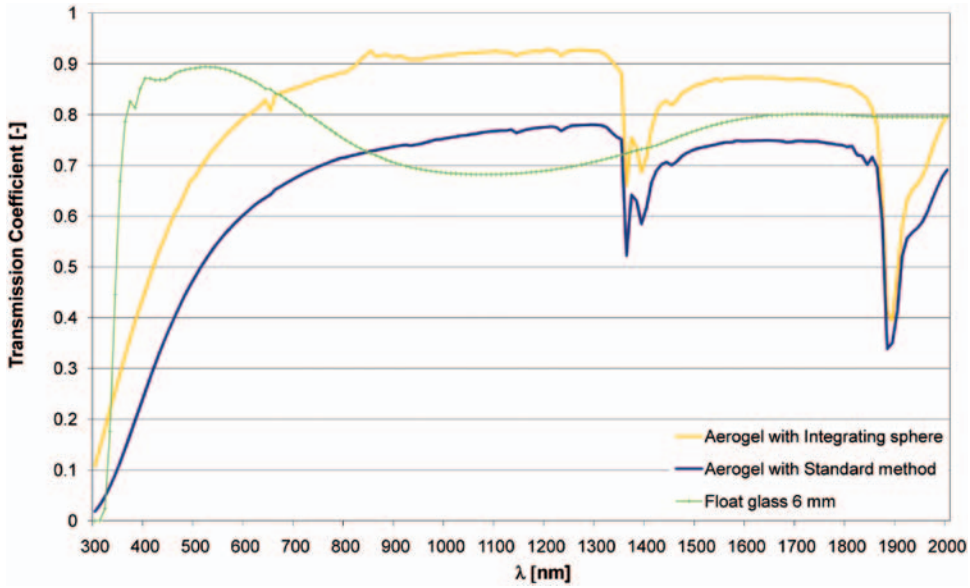

Fig. 3. Transmission coefficient vs. wavelength of pane aerogel measured without the integrating sphere (standard method) and with the integrating sphere compared to a 6 mm float glass.

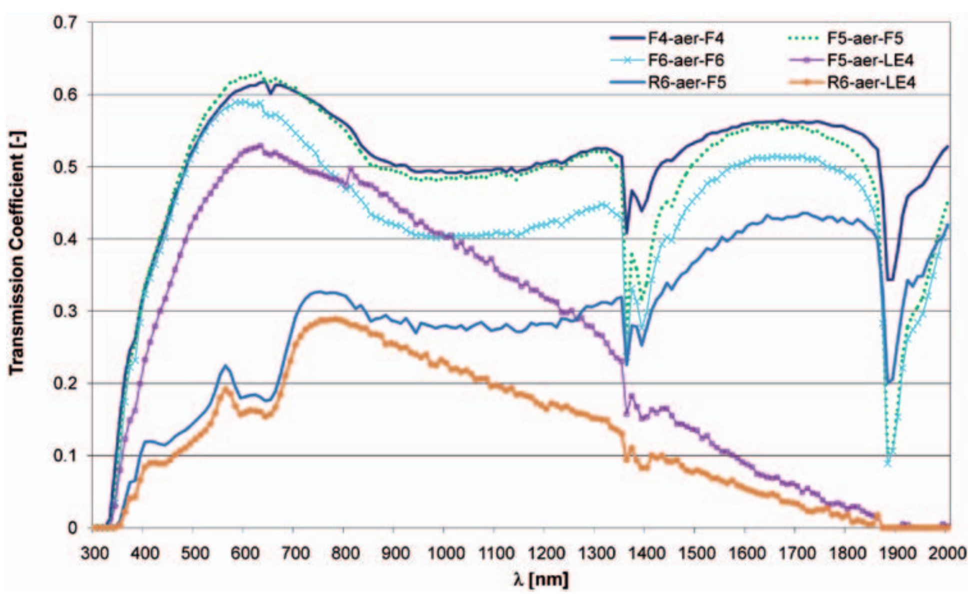

Fig. 4. Transmission coefficient vs. wavelength for samples with aerogel pane in the interspace.

Figure 5 also shows the results for three samples covered by the same (external and inner) glass layers of 5 mm. The increasing of the interspace would give a reduction of the spectral transmission coefficient. The difference between the step from 10 to 15 mm (about 0.1) was shown to be greater than the difference between the step from 8 to 10 mm (about 0.05). Finally, sample F5-gr10-LE4 is also reported in Figure 5; it shows the same behaviour as samples with pane aerogel, due to low e-coated glass in internal side (Figure 4).

Figure 6 shows the results related to samples with capillary TIM in the interspace. The data illustrate similar trends for all the samples, with a high reduction of the transmission coefficient due to the increasing thickness of

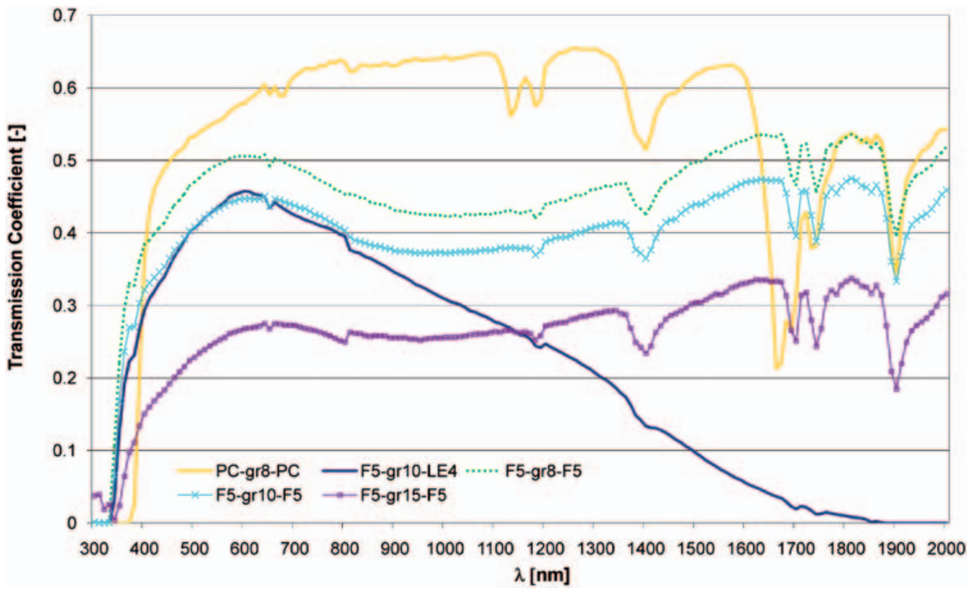

Fig. 5. Transmission coefficient vs. wavelength of five significant samples with granular aerogel in the interspace.

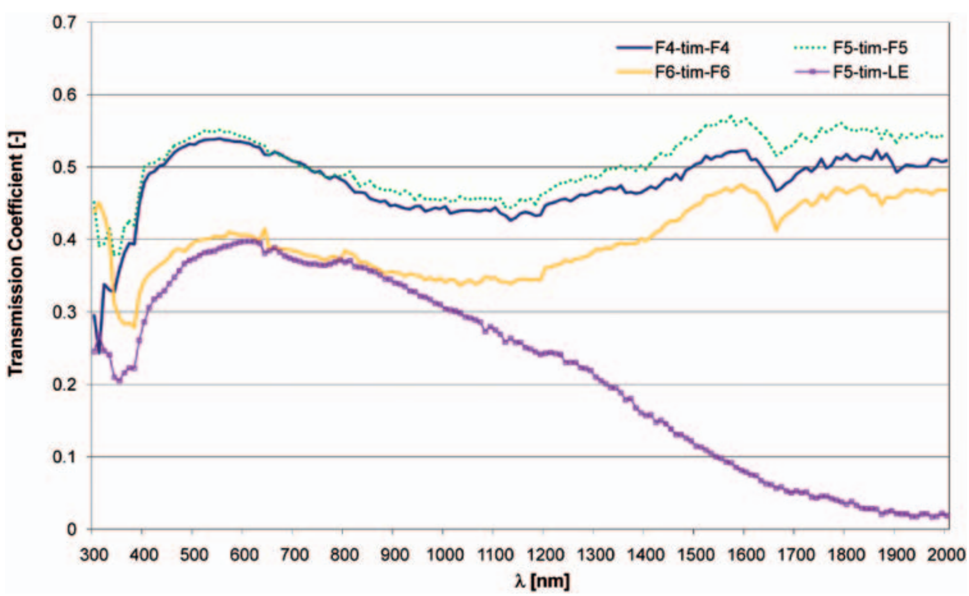

Fig. 6. Transmission coefficient vs. wavelength of the samples with capillary TIM in the interspace.

the glasses, except for sample F5-tim-LE4, characterised by the internal low e-coated glass, as in the other cases.

The results about the reflection coefficients are reported, as an example, in Figure 7, for some samples with aerogel in interspace.

The lighting (τ_v and ρ_v) and solar (τ_e, ρ_e and α_e) characteristics of the samples were calculated, in compliance with the European Standard UNI EN 410/2000 [26]. In particular, the light transmittance of a sample was calculated using Equation (1):

$$\tau_v = \frac{\sum_{\lambda=380}^{780} D_\lambda \tau(\lambda) V(\lambda) \Delta\lambda}{\sum_{\lambda=380}^{780} D_\lambda V(\lambda) \Delta\lambda} \tag{1}$$

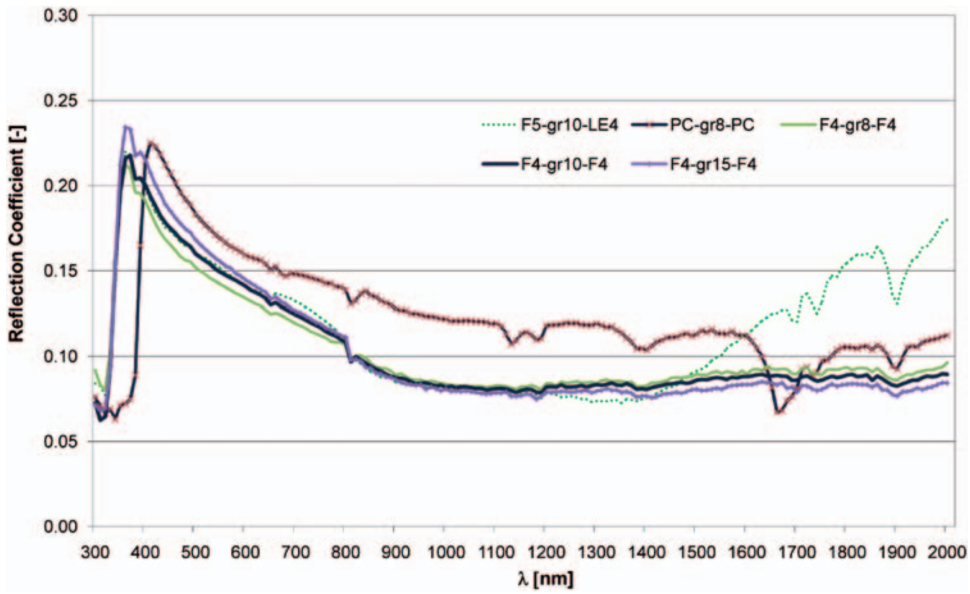

Fig. 7. Reflection coefficient vs. wavelength for some samples with aerogel in interspace.

in which D_λ is the relative spectral distribution of illuminant D_{65} (given by the Norm); $\tau(\lambda)$ the spectral transmittance of the sample; $V(\lambda)$ the spectral luminous efficiency for photopic vision defining the standard observer for photometry (given by the Norm); $\Delta\lambda$ the wavelength interval (10 nm).

A similar equation was used to calculate ρ_v, but the spectral reflection $\rho(\lambda)$ instead of $\tau(\lambda)$ was considered. The solar direct transmittance τ_e was calculated using Equation (2):

$$\tau_e = \frac{\sum_{\lambda=300\text{ nm}}^{2500} S_\lambda \tau(\lambda)\Delta\lambda}{\sum_{\lambda=300\text{ nm}}^{2500} S_\lambda \Delta\lambda} \quad (2)$$

where S_λ is the relative spectral distribution of the solar radiation; the values of the term $S_\lambda\Delta\lambda$ are given by the norm.

Finally, the solar direct absorbance α_e was calculated using Equation (3) [26]:

$$\alpha_e = 1 - \tau_e - \rho_e \quad (3)$$

In Table 2, the optical properties of the proposed samples are reported. The values of lighting transmittance τ_v were in the 0.16–0.59 range. The lower values of τ_v and τ_e were related to samples with reflecting coatings; they could be used in very hot climates, where there is a need to reduce solar heat transmission, especially in office buildings where large transparent surfaces are fitted. The reflection properties are similar even if the material in the interspace is different, because they depend above all on the characteristics of the external glazing slab.

Evaluation of Sample Performance and Comparison to Conventional Windows: Results and Discussion

In order to compare the performance of the different samples, depending on the variety of filling, three important parameters were considered: τ_v, g and U-value. The light transmittance τ_v (see further) would represent the glazing system capacity to diffuse the natural light indoors. This is important since the natural light would concur to save electric energy in the daytime, but could affect general health of human beings. The g and U, instead, would 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 [26], 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 (Figure 8) as defined by Equation (4):

$$g = \tau_e + q_i \quad (4)$$

Table 2. Optical properties of the samples calculated in compliance with UNI EN 410/2000

Sample	τ_v	ρ_v	τ_e	ρ_e	α_e
F4-aer-F4	0.58	0.15	0.51	0.14	0.35
F5-aer-F5	0.59	0.14	0.51	0.12	0.37
F6-aer-F6	0.57	0.14	0.46	0.12	0.42
F5-aer-LE4	0.48	0.15	0.39	0.13	0.48
R6-aer-F5	0.18	0.34	0.23	0.26	0.51
R6-aer-LE4	0.16	0.34	0.17	0.26	0.57
PC-gr8-PC	0.56	0.17	0.55	0.15	0.30
F5-gr10-LE4	0.44	0.15	0.34	0.13	0.53
F4-gr8-F4	0.50	0.14	0.44	0.12	0.44
F4-gr10-F4	0.42	0.15	0.37	0.13	0.50
F4-gr15-F4	0.27	0.15	0.24	0.13	0.63
F5-gr8-F5	0.49	0.15	0.45	0.13	0.42
F5-gr10-F5	0.43	0.15	0.39	0.13	0.48
F5-gr15-F5	0.25	0.12	0.24	0.11	0.65
F6-gr8-F6	0.45	0.16	0.36	0.13	0.51
F6-gr10-F6	0.44	0.15	0.34	0.12	0.54
F6-gr15-F6	0.27	0.15	0.23	0.12	0.65
F4-tim-F4	0.540	0.105	0.490	0.095	0.415
F5-tim-F5	0.550	0.110	0.500	0.100	0.400
F6-tim-F6	0.400	0.106	0.380	0.093	0.527
F5-tim-LE4	0.390	0.110	0.320	0.100	0.580

where q_i would depend on the heat transfer by convection and the solar direct absorbance, α_e, of the samples.

The *U*-value was calculated in compliance with the standard method described in the technical norm UNI ISO 673 [28], 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 calculated would refer the thermal characteristic in the centre of glazing, excluding the frame and dividers effects.

A comparison for the samples characterised by the same inner and external slab (float glass 4 mm) was carried out, by varying the filling; in addition to that, "conventional" double and triple glazing windows were considered.

The solar factor *g* was calculated from the measurement results in compliance with UNI EN 410, considering the sample with monolithic aerogel in interspace as an evacuated triple glazing. Finally, the thermal transmittance (*U*-value) for the samples with aerogel was calculated, according to the standard [28]; for the thermal conductivity, a value of $0.010\,\mathrm{W \cdot m^{-1} \cdot K^{-1}}$ was assigned to monolithic aerogel, corresponding to evacuated aerogel glazing at a pressure of 10 hPa [16,20], while for granular aerogel $0.018\,\mathrm{W \cdot m^{-1} \cdot K^{-1}}$ was considered [21]. For the thermal transmittance of the sample with capillary TIM data from literature were considered [22]. The results are shown in Figure 9.

For the sample with the monolithic aerogel, the evacuated glazing systems would allow the achievement of a calculated *U*-value little higher than $0.6\,\mathrm{W \cdot m^{-2} \cdot K^{-1}}$, while the light transmittance calculated using Equation (1) from the experimental data would be equal to 0.58 and the calculated solar factor would be 0.70. These data were consistent with the experimental values obtained in the literature [16]. For the granular aerogel glazing unit, a calculated *U*-value little higher than $1\,\mathrm{W \cdot m^{-2} \cdot K^{-1}}$ and a calculated solar factor equal to 0.32 were obtained, but the light transmittance was lower than 0.30. Finally, the thermal transmittance *U* for the capillary TIM sample was about $1.3\,\mathrm{W\ m^{-2} \cdot K^{-1}}$, the τ_v was equal to 0.54 and the solar factor was 0.58.

The most promising of the examined materials was the monolithic aerogel, which gave a better light transmittance as compared with the others and, if inserted in a double glazing, very low *U*-values would be obtained with lower glass thickness and much lighter density. The capillary TIM would be used in particular conditions, such as office buildings in hot climates, where direct sunlight must be avoided and an illumination of the room with daylight is preferred, thus significantly reducing glare problems.

A global evaluation of the improvements due to the use of the innovative materials was carried out and was compared with the performance of windows normally used in Italy and in the EU countries, in order to comply with

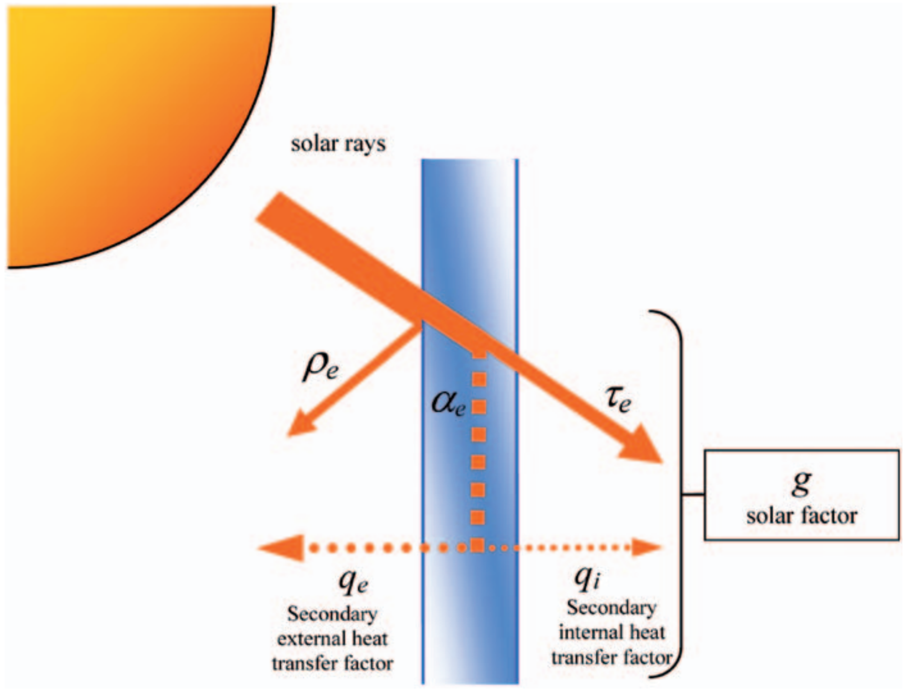

Fig. 8. Determination of the solar factor.

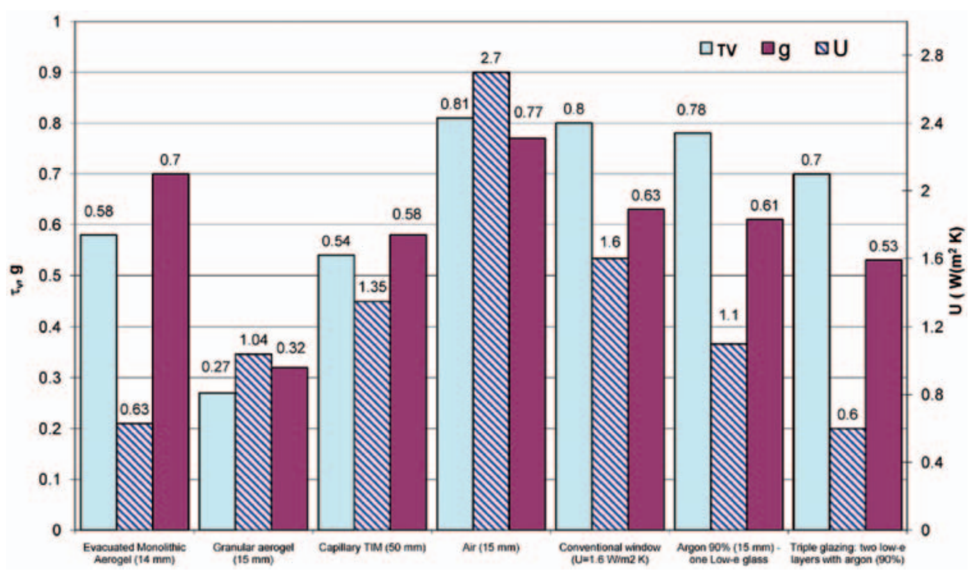

Fig. 9. Comparison between the performance of samples characterised by the same inner and external slab (float glass 4 mm) and conventional windows.

the regulation limits (Figure 9). For these "conventional" glazing units, literature data were considered [29,30]: light transmittance τ_v equal to 0.8, solar transmittance τ_e equal to 0.53, solar factor g equal to 0.63 and thermal transmittance U equal to $1.6\,W \cdot m^{-2} \cdot K^{-1}$.

The innovative glazing would reduce the visible transmittance of about 28% for the monolithic aerogel samples and of 33% for the capillary TIM samples. The reduction would equal to 66% for the samples with granular aerogel in interspace (thickness of 15 mm).

Furthermore, introducing monolithic aerogel in the same thickness interspace instead of air, the thermal transmittance would vary from 2.7 to $0.6\,W \cdot m^{-2} \cdot K^{-1}$.

The most recent European [31] and Italian Laws [32] and technical references [29] suggest further strict limits for thermal transmittance values to be imposed for window glazing. Starting from the year 2011, the *U*-values for the *F* zone (the coldest zone in Italy) will be lower than $1.3\,W \cdot m^{-2} \cdot K^{-1}$: this goal can be obtained just using double glazing with argon gas filled in the interspace (air space thickness = 15 mm) coupled with low-e coated glasses (surface emissivity <0.1), which have a *U*-value of $1.1\,W \cdot m^{-2} \cdot K^{-1}$. If the thermal transmittance should be further reduced to $0.6\,W \cdot m^{-2} \cdot K^{-1}$, 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 would increase by one-third. Therefore, the glazing systems studied in this paper are very promising: a *U*-value of about $0.6\,W \cdot m^{-2} \cdot K^{-1}$ was obtained with evacuated aerogel glazing, with a reduction of the light transmittance of about 17% with respect to a triple-layer glazing with the same *U*-value. The solar factor ($g = 0.70$) was similar to the one of a double glazing with air in interspace. A solar factor of 0.5 was obtained only with triple glazing, but in cold climates, this would not be convenient because the increasing of heat insulation would be thwarted by the decreasing of *g*-value. The final result was shown to be the same, but the triple glazing system would be a more expensive option [16].

Conclusion

In the past few years, glazing systems with innovative TIMs were investigated, showing the silica aerogel as a promising material for applications in building envelope because of its high light and solar energy transmittance and its low thermal conductivity.

This paper evaluated the energetic and luminous characteristics of TIMs, in particularly considering their use in buildings, as a substitution for double-glazed windows normally used in Italy and in the EU countries, in order to comply with the requirements of the regulations. Several innovative glazing systems with silica aerogel, monolithic and granular form, and capillary TIM in interspace were characterised in this study and compared with the characteristics of "conventional" glazing units.

Firstly, the optical properties of single panes of aerogel were measured, evaluating the spectral transmittance versus the wavelength, using a spectrophotometer Cary 2300 equipped with the integrating sphere, necessary for reliable measurements of the diffusive materials.

The better performance between the investigated materials was given by monolithic aerogel (Figure 8). The results showed a 60% reduction in heat losses ($U = 0.63\,W \cdot m^{-2} \cdot K^{-1}$) with only a 27% reduction in light transmittance as compared to the "conventional" double glazing with a low-e layer. For the granular systems, the light reduction would be about 70% and the *U*-value would be a little higher than $1\,W \cdot m^{-2} \cdot K^{-1}$ with the same total thickness.

The monolithic aerogel innovative glazing systems would allow energy savings in buildings and represent a concrete alternative to the "conventional" windows when very strict limits are imposed by the EU building regulations or by the requirements in highly glazed buildings. Also, capillary TIM systems can be employed in particular conditions (i.e. non-residential buildings in hot climates), when a reduction of the direct sunlight is required, without reducing the diffuse light in the room.

Moreover, by increasing the thickness of aerogel pane, thinner windows with *U*-values lower than $0.5\,W \cdot m^{-2} \cdot K^{-1}$ would be obtained, without diminishing the solar factor or reducing substantially the daylight factor.

Finally, prototypes of evacuated aerogel windows were realised [16], but these systems have still not been commercialised because of some problems such as the phenomenon of light scattering, which would give a reduced optical quality of vision through the material; furthermore, the production process would be very complex and it would not allow the use of very large sheets, without altering performance [15,16]. Current research has sought to solve these problems, with particular attention to reducing the costs, which is too high for a distribution on a wide scale.

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