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Perspective of aerogel glazings in energy efficient buildings

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ABSTRACT

The application perspective of aerogel glazings in energy efficient buildings has been discussed by evaluating their energy efficiency, process economics, and environmental impact. For such a purpose, prototype aerogel glazing units have been assembled by incorporating aerogel granules into the air cavity of corresponding double glazing units, which enables an experimental investigation on their physical properties and a subsequent numerical simulation on their energy performance. The results show that, compared to the double glazing counterparts, aerogel glazings can contribute to about 21% reduction in energy consumptions related to heating, cooling, and lighting; payback time calculations indicate that the return on investment of aerogel glazing is about 4.4 years in a cold climate (Oslo, Norway); moreover, the physical properties and energy performance of aerogel glazings can be controlled by modifying the employed aerogel granules, thus highlighting their potential over other glazing technologies for window retrofitting towards energy efficient buildings. The results also show that aerogel glazings may have a large environmental impact related to the use of silica aerogels with high embodied energies and potential health, safety and environment hazards, indicating the importance of developing guidelines to regulate the use of aerogel glazings.

1. Introduction

As an important building element in modern architecture, windows allow light, solar energy, and fresh air to promulgate the living area and offer an irreplaceable indoor–outdoor interaction, thus having a huge impact on the occupant comfort. However, the fact that windows are usually made of clear glass may bring with some drawbacks, such as glare and solar overheating, which may degrade the user comfort and increase the energy consumption of buildings [1]. Another issue associated with clear glass windows is their poor thermal insulation performance compared to other building envelope components such as walls or roofs. In general, windows represent a large thermal bridge and can constitute up to 45% of the total energy loss though the building envelope [2]. Consequently, improving the thermal insulation level of windows has without doubt been an important research topic [1–3]. Highly insulating glazing units or windows with *U*-values (heat transfer coefficient) lower than 0.7 W/(m^{2}K) have been under rapid development [2]; commercial products such as multilayered windows [4,5] and aerogel glazings [6–8] have been sold for a wide range of applications, i.e., for both new buildings and window renovations towards energy efficient buildings.

Aerogel glazings are an interesting glazing technology and may address simultaneously the energy efficiency and user comfort requirement placed on windows [6–9]. Aerogel glazings are architecturally similar to the conventional double glazings, where the air cavity between the two clear glass panes is filled with silica aerogels with low thermal conductivities (about 0.013 and 0.020 W/(mK) for monolithic and granular aerogels, respectively) [8,9]. Aerogel glazings have usually a high level of thermal insulation and a typical *U*-value of about 0.6 W/(m^{2}K) can readily be achieved [6–9]. In practice, due to the weak mechanical strength of monolithic aerogel panes [10], aerogel glazings are usually assembled with aerogel granules, which results in translucent glazing units with improved thermal insulation, enhanced light scattering, and reduced sound transmission [11–14]. Aerogel glazings are of

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interest in building applications where an unobstructed outside view is not essential [12].

The potential of aerogel glazings in buildings and related infrastructure industry has widely been addressed [6–9,11–17], mostly from an energy saving perspective. For example, Dowson et al. have recommended aerogel glazings as a potential solution for retrofitting single-glazed windows to reduce the heat loss without detrimental reduction in light transmission [15]. Using a thermal model in a German climate, Reim et al. have calculated the energetic benefit of aerogel glazings to be comparable to triple glazings [16]. More recently, by comparing the energy performance of an office building consisting of different glazing systems, Ihara et al. have revealed the application potential of aerogel glazings in different climates [17]. However, as any other emerging materials or technologies, how aerogel glazings are used in buildings depends on not only their energy saving potentials, but also other factors such as appearance, cost, service time, and maintenance requirement. As a translucent glazing technology, aerogel glazings are different for the normal transparent windows, which may challenge the architects in the design phase. More importantly, the use of silica aerogels – a manufactured nanomaterial – may lead to potential health, safety and environmental (HSE) concerns [18]. Hence, it is very important to evaluate the potential of aerogel glazings from different aspects, such as energy efficiency, process economics, and environmental impact, in order to strengthen the existing advantages while counteracting disadvantages of this emerging glazing technology. Nevertheless, there seems a lack of studies on such an important topic.

In this work, we discuss the application perspective of aerogel glazings in energy efficient buildings by evaluating their energy efficiency, process economics, and environmental impact. For such a purpose, we have assembled aerogel glazing units (AGUs) by incorporating silica aerogel granules into the air cavity of double glazing units (DGUs), which enables a detailed experimental characterization of their physical properties; thereafter, the energy performance of aerogel glazings has been evaluated by numerical simulations. Moreover, the process economics, building integration, and environmental impact of aerogel glazings have also been evaluated. The results reveal that aerogel glazings are promising in energy efficient buildings; however, developing guidelines to regulate the use of aerogel glazings is also very important.

2. Materials and methods

2.1. Assembly of AGUs

Hydrophobic silica aerogel granules were received from PCAS, France, with typical particle sizes of about 3–5 mm, as shown in Fig. 1a. Clear glass panels (float glass, 350 mm × 500 mm × 4 mm)

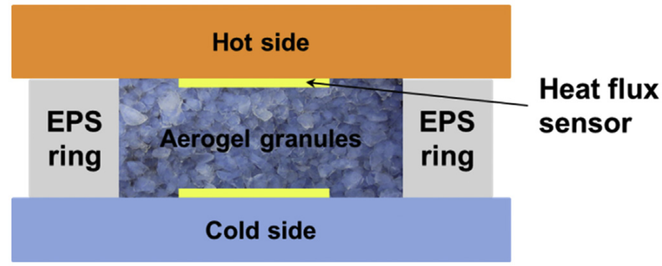

Fig. 2. Experimental setup for the heat flow meter measurements. An EPS (expanded polystyrene) ring is used to enclose the aerogel granules; the measureable dimensions are about 450 mm × 450 mm × 50 mm.

were cleaned with acetone and ethanol to remove the surface contaminations before the assembly of the glazing units. Thermix® TX.N® plus spacer with a gap size of 14 mm was used. Silicon sealant was purchased from Jula AS, Norway, and used as received.

AGUs were assembled by incorporating aerogel granules into the cavity of a double glazing unit made of two clear glass panels (Fig. 1b) [9]. During the assembly process, the glazing unit was subject to mechanical vibration to ensure a compact packing of aerogel granules inside the cavity and thus reduce future subsiding of the aerogel particles, which might create visible air pockets in the top of the inter-pane cavity [9]. The dimension of the glazing aperture was about 475 mm × 325 mm. The as-prepared AGUs were thereafter aged in air at 25 °C for 2 weeks and followed by another 2 week aging at 50 °C to harden completely the silicon sealant. Small sized AGU samples (glazing area ~4 cm^2) were also prepared and used for the optical measurement purpose.

2.2. Characterization

Thermal conductivity of aerogel granules was measured by using a heat flow meter method, which was performed according to ISO 8301 [19] and EN 12667 [20]. As shown in Fig. 2, the sample was enclosed in an EPS (expanded polystyrene) ring and sandwiched between the two heat flux sensors. Preset temperature for the hot (top) and cold side (bottom) was 20 and 0 °C, respectively. Thermal properties (i.e., thermal resistance, conductivity, and transmittance) of the as-prepared AGUs were also evaluated by using the same experimental setup. Here, the AGUs were treated as a homogeneous material system with high thermal resistance, which is similar to that used for vacuum insulation panels [21].

Optical properties (transmittance and reflectance) of the as-prepared glazing units were evaluated from 290 to 2500 nm on a PerkinElmer Lambda 1050 UV/VIS/NIR spectrophotometer with a 150 mm Integrating Sphere Accessory, which operates in double

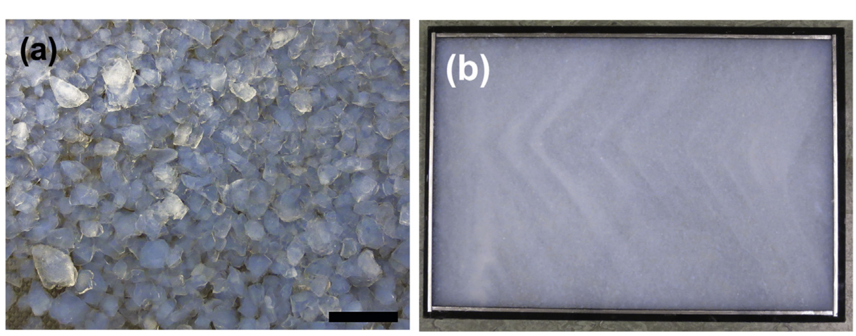

Fig. 1. Photograph of (a) silica aerogel granules and (b) the assembled aerogel glazing unit (dimensions 475 mm × 325 mm). Scale bar in panel a: 10 mm. The wrinkle pattern in the aerogel glazing unit results from the assembly process [9].

beam mode in the specular include (8°/h) or specular exclude (8°/d) geometries. Reflectance spectra were calibrated with a 2.0″ Labsphere diffuse reflectance standard.

2.3. Energy simulation

Energy Plus (version 8) was used to estimate the energy consumption (heating, cooling, and lighting) of an office building located in Oslo. A simplified simulation was used to evaluate the energy performance of different glazing technologies. As shown in Fig. 3, the simplified office model consisted of one story with a heating floor surface area of 784 m^2 and a corresponding heating/cooling air volume of 3136 m^3. Window to wall ratio was set to 32.1% and the total window area was 143.8 m^2. The windows were equally distributed in the east, south, west, and north directions. The window frames were not considered during the energy calculation (i.e., windows have a 100% glazed area); moreover, window shadings were not considered in order to simplify the comparison. The *U*-value of the exterior wall was set to 0.16 W/(m^2K). For the lighting energy calculation, four perimeter zones were modeled, as shown in Fig. 3. When illuminance exceeded 500 lx in a cross point of two diagonal lines of each perimeter zone, artificial lighting was turned off to save the lighting energy. Details of the office model and the related energy calculation were reported previously [17,22].

3. Results and discussion

3.1. Thermal properties of AGUs

Incorporating aerogel granules into the cavity of DGUs improves significantly their thermal insulation level. As shown in Table 1, the assembled AGUs have a typical *U*-value of about 1.19 W/(m^2K), compared to about 2.86 W/(m^2K) for the corresponding DGUs. Such a significant reduction of *U*-values is obviously related to the employed aerogel granules, which reduce the heat transfer through the corresponding DGUs. It is known that, for DGUs, the heat transfer is through conduction (~17%), convection (~17%), and thermal radiation (~66%) [11]; consequently, every individual contribution has to be minimized to achieve thermally insulating glazing units with lower *U*-values. First of all, the presence of aerogel granules inside the air cavity will reduce the conductive heat transfer due to the lower thermal conductivity of aerogels (~0.020 W/(mK)) than that of the normal air (~0.026 W/(mK)). Secondly, small aerogel granules can suppress the airflow loops and reduce significantly the convective heat transfer within the air cavity of DGUs, which has previously been discussed by Ihara et al. [23]. Thirdly, silica has a relatively larger extinction coefficient than that of air [24], which helps to reduce the corresponding radiative heat transfer. With the aforementioned discussions, the better thermal performance of AGUs compared to the corresponding DGUs (Table 1) is understandable.

AGUs have a rather stable thermal performance when compared to that of the corresponding DGUs. For example, horizontal DGUs usually have a larger *U*-value than that of vertically placed DGUs due to the convection effect in the air cavity. In contrast, a previous study indicated that the measured *U*-values of AGUs are almost the same regardless of how AGUs are placed [23]. In this regard, AGUs can be integrated into the building envelope as either conventional vertical windows or tilted roof windows without changing their thermal insulation performance. This may enable AGUs as a multifunctional building envelope component from a viewpoint of architectural design and energy simulation.

Another interesting feature of AGUs is that their thermal performance can be readily controlled by modifying the employed aerogel materials, as revealed by Fig. 4. On the one hand, AGUs with lower *U*-values (i.e., better thermal insulation performance) can be achieved with thicker aerogel granule layers. For example, for a *U*-value of about 0.62 W/(m^2K), the corresponding AGUs can be assembled with a 30-mm-thick layer of aerogel granules with a thermal conductivity of about 0.020 W/(mK); whereas increasing the aerogel layer thickness up to 60 mm will result in an AGU with a *U*-value of about 0.33 W/(m^2K). On the other hand, AGUs with better thermal insulation performance can also be achieved by employing aerogel granules with lower thermal conductivities. For example, at a given insulation layer thickness of about 30 mm, the *U*-value of the corresponding AGUs would be 0.67, 0.62, and 0.54 W/(m^2K) if the thermal conductivity of the employed aerogel granules is 0.023, 0.020, and 0.018 W/(mK), respectively. Employing aerogel granules with lower thermal conductivity is preferred for high performance AGUs with improved process economics (i.e., reduced material use and cost). Since the thermal conductivity of aerogel granules may vary with many factors such as porosity, particle size and packing density [9], further studies on the

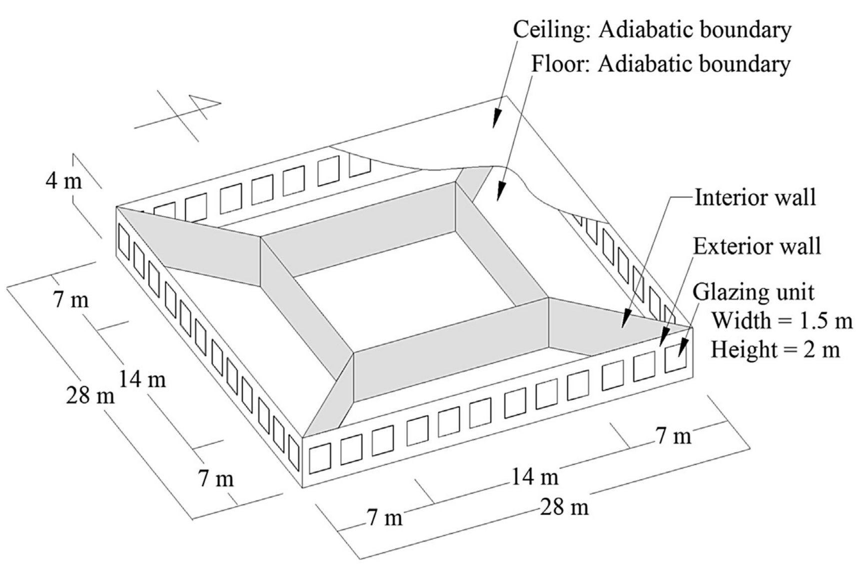

Fig. 3. Schematic drawing of an office building for energy calculations.

Table 1
Thermal performance of aerogel glazing units.

Samples	Thermal conductivity (k, W/(mK))	Thermal resistance (R, m^2K/W)	Thermal transmittance[a] (U, $W/(m^2K)$)
Aerogel granules	0.02	–	–
Float glass	0.98[b]	–	–
AGUs	–	0.67	1.19
DGUs	–	0.18	2.86

[a] Center U-value; the surface thermal resistance of glass pane is set as 0.04 and 0.13 m^2K/W for the exterior and interior side, respectively.
[b] Measured by using a Hot Disk method [9].

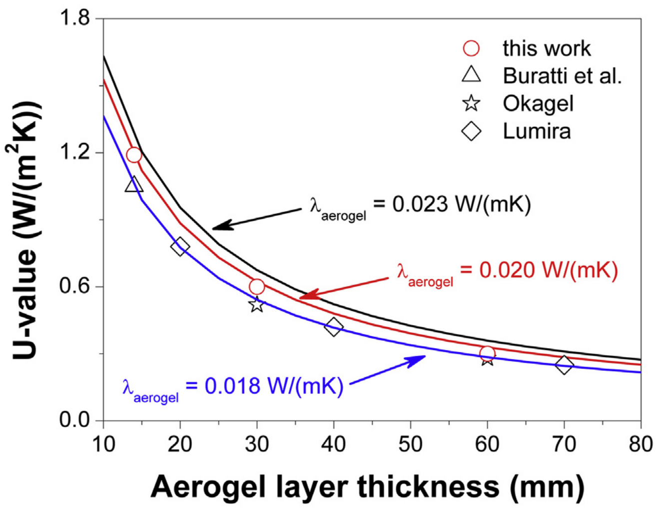

Fig. 4. U-value of AGUs with different thicknesses of the aerogel granule layer (i.e. using different spacers). For the U-value calculations, surface thermal resistance of glass pane is set as 0.04 and 0.13 m^2K/W for the exterior and interior side, respectively. Previous results by Buratti et al. [8] and commercial AGUs from Okagel [11] and Lumira [13] are also included for comparison. The U-value calculations are performed with three types of aerogel granules with different thermal conductivity values.

synthesis of aerogel granules with low thermal conductivities towards window glazing applications are interesting and important.

3.2. Optical properties of AGUs

Incorporating aerogel granules into the air cavity of DGUs changes also significantly their optical properties, which is without doubt an important and fundamental aspect for their applications as window glazings. Traditional clear glass glazings such as DGUs are a typical specular glazing technology, as revealed by the large difference between the corresponding total and diffuse transmittance spectra, Fig. 5a. A specular glazing unit can provide an unblocked view through the window aperture, hence important for the user comfort. However, the specular glazings may also bring with drawbacks such as glare and privacy concerns, therefore requiring further compensation technologies such as shading devices. In contrast, AGUs are translucent and a diffuse glazing technology, as demonstrated by their similar total and diffuse transmittance spectra shown in Fig. 5b. Although AGUs do not offer a clear view through the window aperture, they enable the visible solar radiation to propagate uniformly within the living area, thus minimizing the daylight problems such as high contrast zones (Fig. 6). Diffuse daylight is preferred at many locations and the use of AGUs may therefore be a good alternative to diffusing glass. However, AGUs may have also glare problems [25], especially for those with a slim thickness. The solar radiation that diffuses through the AGUs may result in a shining aperture that can be too bright to look directly at. In this regard, a proper building integration of AGUs is important. For example, the commercial application of AGUs has been focusing on roofs or roof windows [12], where an unobstructed outside view is usually not essential. Alternatively, AGUs can also be integrated at façade spandrels, which may represent a solution form a viewpoint of daylight management and energy savings [17].

The translucent, light diffusing AGUs have also a unique appearance when subjected to different lighting conditions. As shown in Fig. 7a, the transmittance and reflectance spectra of clear glass glazings are featureless. In contrast, AGUs exhibit an intensive violet-blue reflection band (centered at ~ 400 nm) and an orange-red transmission band (centered at ~ 640 nm), Fig. 7b. It indicates that, depending on the lighting conditions, the appearance of AGUs may be either cold, bluish (e.g., in the daytime, Fig. 8a) or warm, yellowish (e.g., in the evening, Fig. 8b), which may represent an interesting feature for architectural design.

3.3. Energy performance of AGUs

It is important to evaluate the energy performance of AGUs since windows usually play a critical role on the energy efficiency of buildings [2,26]. In this work, the energy demands of an office building have been estimated with respect to different window

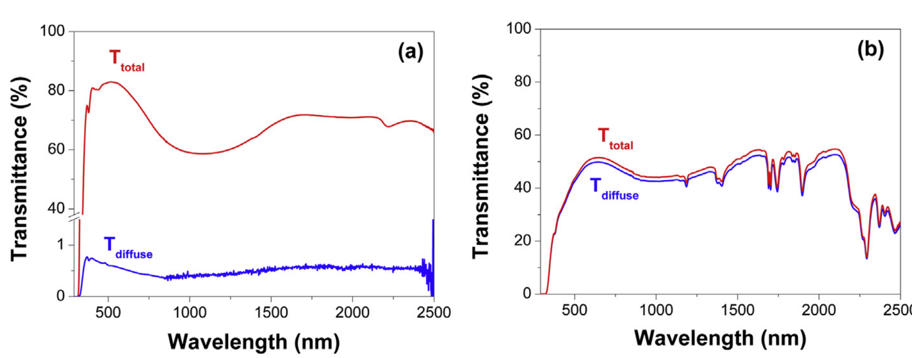

Fig. 5. Total and diffuse transmittance spectra of (a) DGUs and (b) AGUs.

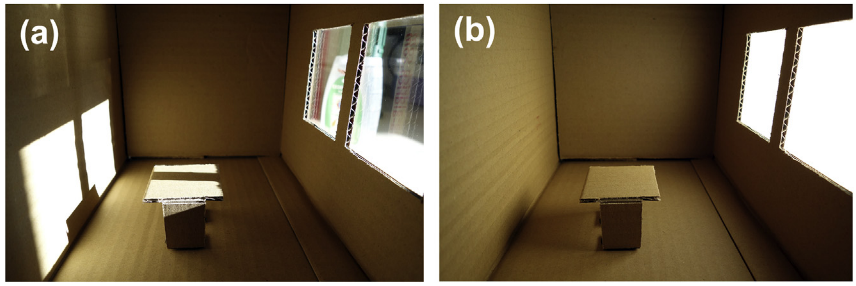

Fig. 6. Comparison between (a) specular DGUs and (b) diffuse AGUs for daylight management by using a cardboard house model.

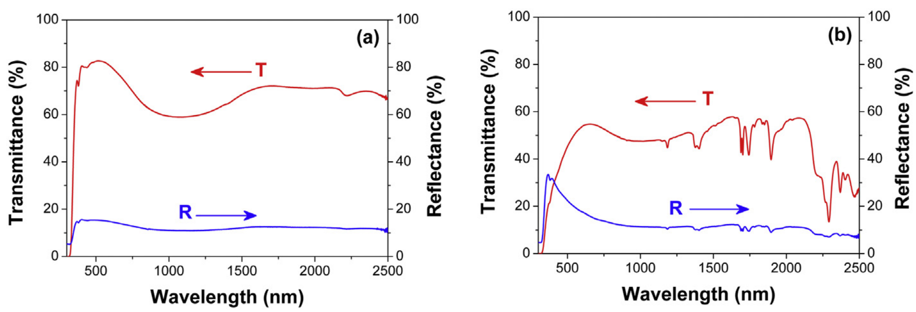

Fig. 7. Total transmittance and reflectance spectra of (a) DGUs and (b) AGUs.

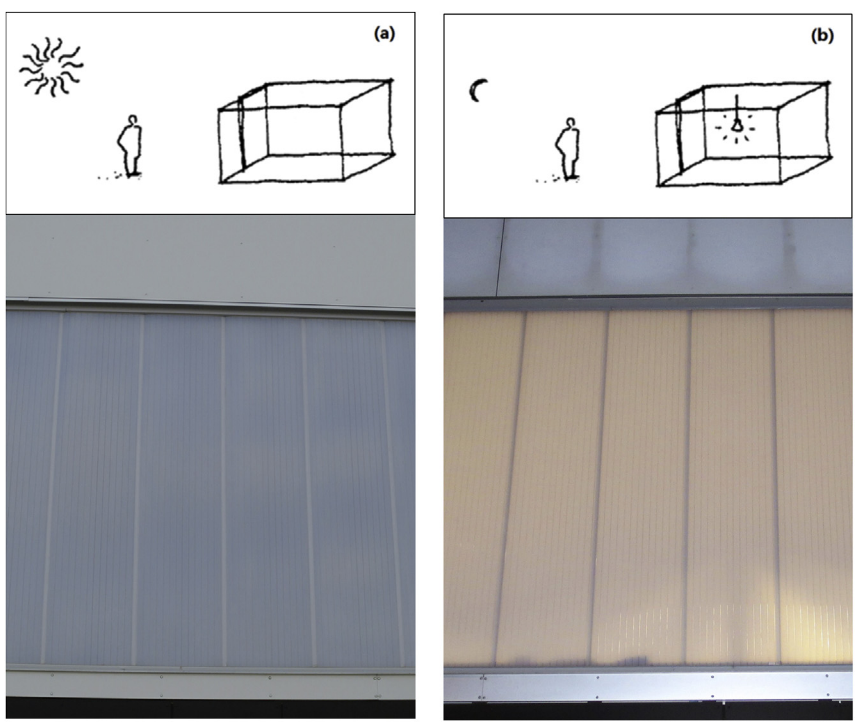

Fig. 8. Appearance of AGUs at different lighting conditions: (a) daytime and (b) evening. In panel b, the lighting devices inside are white fluorescent lamps. Pictures are taken from a commercial building having aerogel windows.

glazings, Fig. 9. Table 2 shows the thermal and solar radiation parameters used for the energy calculations. The relevant solar radiation factors, such as visible solar transmittance T_{vis} and solar factor g (i.e., solar heat gain coefficient, SHGC) have been calculated according to the International Standard ISO 9050 [27]. The calculations might subject to a certain degree of uncertainty since AGUs are a diffusing glazing technology, of which the calculation procedures are not strictly defined by the ISO 9050.

The nature of window glazings affects substantially the energy demand for heating, cooling and lighting, Fig. 9. In general, triple glazing units (TGUs) show the best energy performance with respect to the total energy consumption (Fig. 9d); nevertheless,

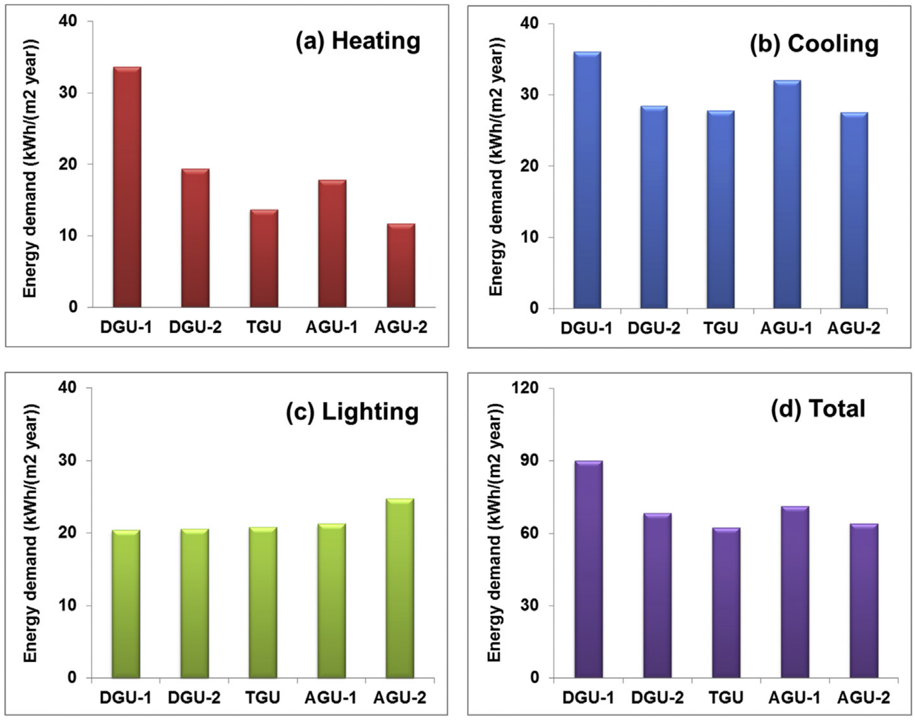

Fig. 9. Energy demands of an office building with different window glazings (location: Oslo, Norway).

Table 2
Thermal and solar radiation parameters of aerogel glazings and multilayered glazings.

Glazings	Configuration[a]	Thermal transmittance[b] (U-value, W/(m^{2}K))	Solar factor (g- value)	Visible solar transmittance (T_{vis})
DGU-1	G/A/G	2.86	0.76	0.81
DGU-2[c]	G/LE/Ar/LE/G	1.20	0.52	0.74
TGU[c]	G/LE/Ar/LE/G/Ar/LE/G	0.70	0.45	0.63
AGU-1	G/AG-14/G	1.19	0.57	0.50
AGU-2	G/AG-30/G	0.60	0.34	0.17

[a] G: float glass, 4 mm. A: air cavity, 14 mm. LE: low emissivity coating, $\varepsilon = 0.071$. Ar: argon, 14 mm cavity. AG-14: aerogel granules in a 14 mm cavity. AG-30: aerogel granules in a 30 mm cavity.
[b] Center U-value.
[c] State-of-the-art multilayered glazings; details are reported in Ref. [3].

AGU-2 possesses a comparable performance to that of TGU [17], and exhibits even better performance with respect to space heating and cooling. A comparison between Fig. 9 and Table 2 indicates that the calculated heating, cooling, and lighting demands are correlated to the U value, solar factor, and visible solar transmittance T_{vis} of the corresponding glazing units, respectively. For example, as shown in Fig. 9a, DGU-1 has the highest heating demand among all tested samples, which corresponds to its highest U value of about 2.86 W/(m^{2}K). Not surprisingly, AGU-2 with the lowest U value of 0.6 W/(m^{2}K) shows also the lowest heating load. The cooling load of the building can partly be attributed to the solar overheating through its windows, of which a small solar factor of the glazing units is preferred to minimize the corresponding cooling demand. For example, AGU-2 shows the lowest cooling demand (Fig. 9b), which can be attributed to its lowest solar factor of about 0.34, compared to about 0.45 for TGU or 0.76 for DGU-1 (see Table 2). One may also notice that AGUs have a higher lighting demand compared to that of the other glazing units (Fig. 9c). This is due to the relatively low T_{vis} of AGUs. For example, AGU-2 has a low T_{vis} of about 0.17, compared to about 0.50 for AGU-1 and 0.63 for TGU (Table 2). This accounts for a higher lighting demand for AGU-2, 24.7 kWh/(m^{2}year), than 21.3 and 20.8 kWh/(m^{2}year) for AGU-1 and TGU, respectively. It is important to note that the energy calculations, especially the lighting demand, may strongly correlate to the users. For example, as shown in Fig. 6, different user comfort and consequently different user behaviors, such as turn on/off shading or artificial lighting, should be properly addressed when comparing different glazing technologies.

In general, AGUs have a better energy performance than the state-of-the-art DGUs, indicating that AGUs can become a solution for retrofitting the existing single-paned or double-paned windows [15]. Moreover, the properties of AGUs can be tailored by controlling the employed aerogel materials (see Fig. 4) [9], which is an advantage of AGUs over other glazing technologies to meet different energy requirements placed on windows.

3.4. Building integration of AGUs

Replacing the traditional clear glass glazings with translucent aerogel glazings is probably a simple practice but does involve many important parameters to be addressed for a successful building integration. As any other building materials or components, how AGUs are used in buildings depends on not only their physical properties (and consequently their functions in buildings), but also other factors such as cost, maintenance requirement, and environmental impact.

AGUs are a translucent glazing technology, which, on the one hand, enables high quality diffuse light to be propagated uniformly within the living area (see, for example, Fig. 6), on the other hand, blocks the view through the window aperture – an important indoor–outdoor interaction. Since both the diffuse light and the clear view are crucial to the user comfort, an improved architectural design is obviously important for the building integration of AGUs. AGUs have been used as roofs or roof windows for large constructions such as office buildings, stadiums, or museums [12], which is very promising form a viewpoint of daylight management and energy savings. However, the economic and aesthetic concerns may have priority when AGUs are used in residential buildings.

The cost issue has to be addressed for any emerging materials or technologies. For AGUs, the incorporation of aerogel granules into DGUs would increase the manufacture cost; nevertheless, the increased cost may be compensated by the energy savings of AGUs during the service (see Fig. 9). The payback time of AGUs can in principle be calculated if the material and energy cost and service life of AGUs are known, Table 3. Although the cost analysis should be treated with caution due to the large uncertainty on the market price for the raw materials and energy [15,28], a longer service life of AGUs, e.g., >10 years, is normally required for their applications. In this regard, addressing the durability issue of AGUs is without doubt very important. As reported previously [9,23], AGUs tend to have a subsidence problem related to the granule packing, which may result in visible air pockets in the top of the inter-pane cavity and decreases the overall performance of AGUs. An improved design is therefore required. Another concern on durability of AGUs is the stability of aerogel granules [29], which are usually treated with a hydrophobic surface to avoid water absorption/condensation. However, aerogel granules may lose, partly or totally, the surface hydrophobicity during the service (e.g., under ultraviolet light irradiation), thus highlighting a need for further investigations [29].

As the concern on embodied energy (EE) or carbon burden of building materials/components has been becoming increasingly important [30], the environmental impact of AGUs, i.e., how the newly introduced AGUs would affect the total CO_2 emission budget of the building, will become an important consideration during the building integration process.

Silica aerogels are a manufactured nanoporous material and characteristic of low density, high porosity, and high surface area, which bring with at least two important environmental features: the high EE of silica aerogels resulting from their energy-intensive manufacture processes [31] and the potential ecotoxicity related to the use and disposal of aerogel materials/products [18]. So far, there are no data available for the corresponding EE and CO_2 burden of silica aerogels. According to a previous study by Dowson et al. [32], the commercial silica aerogel has a production energy of about 53.9 MJ/kg and a CO_2 burden of about 4.3 kgCO_2/kg, excluding the CO_2 used for supercritical drying. Note that these values are much higher than those for conventional mineral insulations with values ranging from 16.6 to 38.8 MJ/kg and 1.1 to 1.4 kgCO_2/kg, respectively [33]. It indicates that the EE of silica aerogels is probably high since

$$EE_{\text{silica aerogels}} = EE_{\text{production process}} + EE_{\text{raw materials}}, \quad (1)$$

where the raw materials for the synthesis of silica aerogels are usually oxosilanes such as tetramethyl orthosilicate and tetraethyl orthosilicate with high EEs and CO_2 burdens [34]. Obviously, the high environmental impact of silica aerogels would increase the EE and CO_2 burdens of the corresponding AGUs. In this regard, for the building applications where the environmental impact has priority, e.g., zero emission buildings [30], the potential of AGUs over other alternative glazing technologies needs to be properly addressed.

The safety issue related to AGUs is also important for their building integration. What makes AGUs a special target of question is related to the use of silica aerogels – a manufactured nanomaterial. Silica aerogels are similar to sand with respect to their chemical composition (i.e., SiO_2); nevertheless, they are different in many ways. The large surface area and high porosity of silica aerogels make them a unique nanostructured material that may have potential HSE risks [18]. At present, the limited data on ecotoxicity of silica aerogel comes from Aspen Aerogels Safety Data Sheet [35], which claims that "*product is not classified as a hazardous material*" and "*dust from the product when handling and in use may cause mechanical irritation to the respiratory tract, eyes and skin*". However, it is probably too risk (or too early) to conclude that silica aerogels are "safe" because the material is amorphous silica, which is in general not recognized as either an animal or human carcinogen [36]. It is important to point out that the toxicity of nanomaterials usually correlates to their compositions, sizes, shapes, and surface properties [37,38]; therefore, the ecotoxicity of silica aerogels should be studied on a case-by-case basis. Moreover, silica aerogels are usually treated with organic chemicals to achieve the surface hydrophobicity [31], which may cause special hazards or HSE concerns related to these organic chemicals. Evidently, the ecotoxicity of silica aerogels is unclear at the moment, thus highlighting a need for further investigations.

The limited knowledge on the HSE risk of silica aerogels makes it problematic to treat the aerogel waste after the service of AGUs. The situation may become even worse when AGUs are accidentally broken during the service (Fig. 10). Alternative materials to glass panes (e.g., polycarbonate board) may have to be considered in practice to reduce the potential hazards of AGUs, for example, when used as a roof window. Therefore, it is very important to develop guidelines to regulate the use and disposal of silica aerogels and AGUs. Moreover, a proper architectural design is without doubt very important for the building integration of AGUs.

4. Conclusions

Aerogel glazing units (AGUs) have been assembled by incorporating silica aerogel granules into the cavity of double glazing units (DGUs). The physical properties, energy performance, process

Table 3
Cost analysis of aerogel glazing units.

Samples	U value(W/(m^{2}K))	Aerogel costs[a] (EUR)	Energy savings[b] (kWh/year)	Payback time[c] (year)
DGU-1	2.86	0	0[d]	0[d]
AGU-1	1.19	8052	14 896	4.4
AGU-2	0.60	17 256	21 168	6.7

[a] The cost of aerogel granules is set as 4000 EUR/m^3. The window area is 143.8 m^2.
[b] The floor area is 784 m^2.
[c] Assuming an energy price of 0.15 EUR/kWh in Oslo. Coefficient of performance is not considered for simplification.
[d] DGU-1 is treated as the reference.

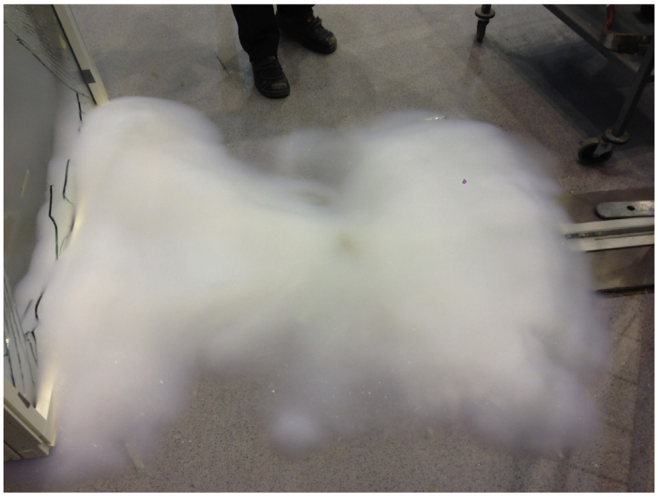

Fig. 10. Photograph of an accidentally broken AGU. Aerogel granules have been scattered in a large area.

economics, and environmental impact of AGUs have been studied in order to evaluate the potential of AGUs in energy efficient buildings. Three main conclusions have been drawn:

(1) AGUs are a promising glazing technology from the viewpoint of energy savings. Compared to the DGU counterparts, AGUs can have about 58% reduction in heat loss, which corresponds to about 21% reduction in total energy consumption (heating, cooling, and lighting) in a cold climate (Oslo, Norway). Moreover, physical properties and consequently energy performance of AGUs can be controlled by means of modifying the employed silica aerogel materials, thus highlighting their potential for retrofitting the existing single-paned or double-paned windows towards energy efficient buildings.
(2) AGUs are an interesting solution for daylight management in buildings. AGUs can provide high quality diffuse light that is important to user comfort. However, a proper design and building integration of AGUs are required to minimize the potential hazards of AGUs.
(3) AGUs may have a large environmental impact with respect to their high embodied energy and CO_2 burdens. Moreover, there are potential health, safety and environment risks of AGUs. It is very important to develop guidelines to regulate the use and disposal of silica aerogels and AGUs for their application in buildings.

Further studies are still necessary for the practical application of AGUs, in order to strengthen the existing advantages while counteract the disadvantages of this emerging glazing technology. For example, it is interesting and important to investigate the user-glazing interactions to understand the user comfort with respect to different glazing technologies. We are currently working on these topics and encourage also results from other research groups.

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References

[1] B.P. Jelle, A. Hynd, A. Gustavsen, D. Arasteh, H. Goudey, R. Hart, Fenestration of today and tomorrow: a state-of-the-art review and future research opportunities, Sol. Energy Mater. Sol. Cells 96 (2012) 1–28, http://dx.doi.org/10.1016/j.solmat.2011.08.010.
[2] A. Gustavsen, S. Grynning, D. Arasteh, B.P. Jelle, H. Goudey, Key elements of and material performance targets for highly insulating window frames, Energy Build. 43 (2011) 2583–2594, http://dx.doi.org/10.1016/j.enbuild.2011.05.010.
[3] B.P. Jelle, Solar radiation glazing factors for window panes, glass structures and electrochromic windows in buildings – Measurement and calculation, Sol. Energy Mater. Sol. Cells 116 (2013) 291–323, http://dx.doi.org/10.1016/j.solmat.2013.04.032.
[4] A. Roos, B. Karlsson, Optical and thermal characterization of multiple glazed windows with low U-values, Sol. Energy 52 (1994) 315–325, http://dx.doi.org/10.1016/0038-092X(94)90138-4.
[5] H. Karabay, M. Arıcı, Multiple pane window applications in various climatic regions of Turkey, Energy Build. 45 (2012) 67–71, http://dx.doi.org/10.1016/j.enbuild.2011.10.020.
[6] M. Reim, A. Beck, W. Körner, R. Petricevic, M. Glora, M. Weth, T. Schliermann, J. Fricke, C. Schmidt, F.J. Pötter, Highly insulating aerogel glazing for solar energy usage, Sol. Energy 72 (2002) 21–29, http://dx.doi.org/10.1016/S0038-092X(01)00086-X.
[7] K.I. Jensen, J.M. Schultz, F.H. Kristiansen, Development of windows based on highly insulating aerogel glazings, J. Non-Crystalline Solids 350 (2004) 351–357, http://dx.doi.org/10.1016/j.jnoncrysol.2004.06.047.
[8] C. Buratti, E. Moretti, Experimental performance evaluation of aerogel glazing systems, Appl. Energy 97 (2012) 430–437, http://dx.doi.org/10.1016/j.apenergy.2011.12.055.
[9] T. Gao, B.P. Jelle, T. Ihara, A. Gustavsen, Insulating glazing units with silica aerogel granules: the impact of particle size, Appl. Energy 128 (2014) 27–34, http://dx.doi.org/10.1016/j.apenergy.2014.04.037.
[10] T. Woignier, J. Phalippou, M. Pradhan, Glasses from aerogels. Part 2. The aerogel-glass transformation, J. Mater. Sci. 25 (1990) 3118–3126, http://dx.doi.org/10.1007/BF00587660.
[11] F. Schneider, OKAGEL: high insulating day lighting systems, in: M.A. Aegerter, et al. (Eds.), Aerogel Handbook - Advances in Sol-gel Derived Materials and Technologies, Springer Science+Business Media, LLC, 2011, pp. 879–888, http://dx.doi.org/10.1007/978-1-4419-7589-8_41.
[12] www.cabot-corp.com/Aerogel/Daylighting/Project-Gallery (accessed on Sept. 29, 2014).
[13] C. Buratti, E. Moretti, Nanogel windows, in: F. Pacheco Torgal, et al. (Eds.), Nearly Zero Energy Building Refurbishment, Springer-Verlag, London, 2013, pp. 555–582, http://dx.doi.org/10.1007/978-1-4471-5523-2_20.
[14] F. Cotana, A.L. Pisello, E. Moretti, C. Buratti, Multipurpose characterization of glazing systems with silica aerogel: in-field experimental analysis of thermal-energy, lighting and acoustic performance, Build. Environ. 81 (2014) 92–102, http://dx.doi.org/10.1016/j.buildenv.2014.06.014.
[15] M. Dowson, D. Harrison, S. Craig, Z. Gill, Improving the thermal performance of single-glazed windows using translucent granular aerogel, Int. J. Sustain. Energy 4 (2011) 266–280, http://dx.doi.org/10.1080/19397038.2011.558931.
[16] M. Reim, A. Beck, W. Korner, R. Petricevic, M. Glora, M. Weth, T. Schliermann, J. Fricke, C. Schmidt, F.J. Potter, Highly insulating aerogel glazing for solar energy usage, Sol. Energy 72 (2002) 21–29, http://dx.doi.org/10.1016/S0038-092X(01)00086-X.
[17] T. Ihara, T. Gao, S. Grynning, B.P. Jelle, A. Gustavsen, Aerogel granulate glazing facades and their application potential from an energy saving perspective, Appl. Energy 142 (2015) 179–191, http://dx.doi.org/10.1016/j.apenergy.2014.12.053.
[18] J. Lee, S. Mahendra, P.J.J. Alvarez, Nanomaterials in the construction industry: a review of their applications and environmental health and safety considerations, ACS Nano 4 (2010) 3580–3590, http://dx.doi.org/10.1021/nn100866w.
[19] ISO 8301 Thermal insulation, Determination of Steady-state Thermal Resistance and Related Properties - Heat Flow Meter Apparatus, 1991.
[20] 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, 2001.
[21] E. Wegger, B.P. Jelle, E. Sveipe, S. Grynning, A. Gustavsen, R. Baetens, J.V. Thue, Aging effects on thermal properties and service life of vacuum insulation panels, J. Build. Phys. 35 (2011) 128–167, http://dx.doi.org/10.1177/1744259111398635.
[22] National Renewable Energy Laboratory, Commercial Buildings Research and Software Development, OpenStudio Version 1.10, 2013 openstudio.nrel.gov [accessed 03.01.14].
[23] T. Ihara, S. Grynning, T. Gao, A. Gustavsen, B.P. Jelle, Impact of convection on thermal performance of aerogel granulate glazing systems, Energy Build. 88 (2015) 165–173, http://dx.doi.org/10.1016/j.enbuild.2014.12.001.
[24] G. Wei, Y. Liu, X. Zhang, X. Du, Radiative heat transfer study on silica aerogel and its composite insulation materials, J. Non-Crystalline Solids 362 (2013) 231–236, http://dx.doi.org/10.1016/j.jnoncrysol.2012.11.041.
[25] B.S. Matusiak, Glare from a translucent façade, evaluation with an experimental method, Sol. Energy 97 (2013) 230–237, http://dx.doi.org/10.1016/j.solener.2013.08.009.
[26] C. Buratti, E. Belloni, D. Palladino, Evolutive housing system: refurbishment with

new technologies and unsteady simulations of energy performance, Energy Build. 74 (2014) 173–181, http://dx.doi.org/10.1016/j.enbuild.2014.01.046.
[27] ISO 9050 Glass in building, Determination of Light Transmittance, Solar Direct Transmittance, Total Solar Energy Transmittance, Ultraviolet Transmittance and Related Glazing Factors, 2003.
[28] E. Cuce, P.M. Cuce, C.J. Wood, S.B. Riffat, Toward aerogel based thermal superinsulation in buildings: a comprehensive review, Renew. Sustain. Energy Rev. 34 (2014) 273–299, http://dx.doi.org/10.1016/j.rser.2014.03.017.
[29] T. Ihara, B.P. Jelle, T. Gao, A. Gustavsen, Aerogel granule aging driven by moisture and solar radiation, Energy Build. 103 (2015) 238–248, http://dx.doi.org/10.1016/j.enbuild.2015.06.017.
[30] A.M.H. Wiberg, L. Georges, T.H. Dokka, M. Haase, B. Time, A.G. Lien, S.E. Mellegård, M.M. Maltha, A net zero emission concept analysis of a single-family house, Energy Build. 74 (2014) 101–110, http://dx.doi.org/10.10167/j.enbuild.2014.01.037.
[31] A. Soleimani Dorcheh, M.H. Abbasi, Silica aerogel; synthesis, properties and characterization, J. Mater. Process. Technol. 199 (2008) 10–26, http://dx.doi.org/10.1016/j.jmatprotec.2007.10.060.
[32] M. Dowson, M. Grogan, T. Birks, D. Harrison, S. Craig, Streamlined life cycle assessment of transparent silica aerogel made by supercritical drying, Appl. Energy 97 (2012) 396–404, http://dx.doi.org/10.1016/j.apenergy.2011.11.047.
[33] G. Hammond and C. Jones. "Inventory of Carbon and Energy (ICE), Version 1.6a", University of Bath, UK. www.ecocem.ie/downloads/Inventory_of_Carbon_and_Energy.pdf [accessed 03.03.15].
[34] R.D. Schlanbusch, B.P. Jelle, L.I.C. Sandberg, S.M. Fufa, T. Gao, Integration of life cycle assessment in the design of hollow silica nanospheres for thermal insulation applications, Build. Environ. 80 (2014) 115–124, http://dx.doi.org/10.1016/j.buildenv.2014.05.010.
[35] Aspen Aerogels. "Pyrogel® XT – Safety Data Sheet", Revision Date: 07/23/2012, http://www.aerogel.com/_resources/common/userfiles/file/Data%20Sheets/Pyrogel_XT_MSDS.pdf [accessed 03.03.15].
[36] J.K. McLaughlin, W.H. Chow, L.S. Levy, Amorphous silica: a review of health effects from inhalation exposure with particular reference to cancer, J. Toxicol. Environ. Health 50 (1997) 553–566, http://dx.doi.org/10.1080/15287399709532054.
[37] N. Feliu, B. Fadeel, Nanotoxicology: no small matter, Nanoscale 2 (2010) 2514–2520, http://dx.doi.org/10.1039/c0nr00535e.
[38] R.D. Handy, R. Owen, E. Valsami-Jones, The ecotoxicology of nanoparticles and nanomaterials: current status, knowledge gaps, challenges, and future needs, Ecotoxicology 17 (2008) 315–325, http://dx.doi.org/10.1007/s10646-008-0206-0.