Applied Energy 128 (2014) 27–34

Contents lists available at ScienceDirect

Applied Energy

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

Insulating glazing units with silica aerogel granules: The impact of particle size

Tao Gao [a,*], Bjørn Petter Jelle [b,c], Takeshi Ihara [a,d], Arild Gustavsen [a]

[a] Department of Architectural Design, History and Technology, Norwegian University of Science and Technology (NTNU), Trondheim, Norway
[b] Department of Materials and Structures, SINTEF Building and Infrastructure, Trondheim, Norway
[c] Department of Civil and Transport Engineering, Norwegian University of Science and Technology (NTNU), Trondheim, Norway
[d] Takenaka Corporation, Osaka, Japan

HIGHLIGHTS

- Aerogel glazing units are assembled with aerogel granules.
- Aerogel glazing units are thermally insulating and light diffusing.
- Properties of aerogel glazing units depend on the particle size of aerogel granules.

ARTICLE INFO

Article history:
Received 15 January 2014
Received in revised form 27 March 2014
Accepted 10 April 2014
Available online 8 May 2014

Keywords:
Silica aerogel
Aerogel glazing
Thermal insulation
Optical property
Particle size
Durability

ABSTRACT

Innovative glazing units with improved thermal and optical performance are important for energy saving in buildings. In this work, light diffusing and thermally insulating aerogel glazing units (AGUs) have been assembled by incorporating silica aerogel granules into the cavity of double glazing units. Experimental results indicate that the optical and thermal properties of AGUs are significantly affected by the particle size of the employed aerogel granules. With respect to a conventional double glazing, a 58% reduction in heat losses and a 38% reduction in light transmittance are achieved by AGUs with large aerogel granules (particle size 3–5 mm); for AGUs with small sized aerogel granules (particle size <0.5 mm), the reduction is 63% in heat losses, but 81% in light transmittance. Moreover, the durability of AGUs depends also on the particle size of the employed aerogel granules. The importance of the particle size issue calls for an optimization of not only the synthesis of aerogel granules, but also the assembly of high performance AGUs towards practical applications.

1. Introduction

Windows as an important building element 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. On the other hand, windows have also a large impact on the energy efficiency of buildings, i.e., up to ~50% of the total energy loss through the building envelope coming actually from its windows [1]. This is due to the large thermal transmittance (i.e. *U*-value) of windows compared to those of other building envelope components such as walls or roofs. For example, walls have typical *U*-values of about 0.1–0.2 W/(m^2 K), whereas the state-of-the-art double glazed windows today have usually a *U*-value of about 1.2 W/(m^2 K) [1,2]. In this regard, improving the insulation level of windows has without doubt been an important research topic [2]. So far, several window innovations, such as multilayered windows [1–6], vacuum windows [7–11], and aerogel windows [12–20], have been under rapid development, with an aim to produce highly insulating glazing units (IGUs) with *U*-values of about 0.5–0.7 W/(m^2 K) to meet the requirement of energy efficient buildings [3,4].

IGUs with *U*-values of about 0.5–0.7 W/(m^2 K) may now be achieved with several different window technologies. For example, multilayered glazings with typically three layers of glass, two low-emissivity (low-e) coatings and low-conductivity gas filling can achieve a *U*-value of about 0.5 W/(m^2 K) [1,2]. Nevertheless, the use of an additional glass layer would increase the weight of the glazing unit by 33% and requires therefore wider and stronger window frames than those for the double glazings. In addition, the decrease of visible transmittance due to the additional glass layer and the low-e coatings represents another drawback [2]. IGUs with

* Corresponding author. Tel.: +47 99895405.
E-mail address: tao.gao@ntnu.no (T. Gao).

http://dx.doi.org/10.1016/j.apenergy.2014.04.037
0306-2619/

U-values of about 0.5–0.7 W/(m^2 K) may also be achieved with vacuum glazings [10,11], which normally consist of two glass panes separated by means of regular distributed small pillars with height less than 1 mm; the edges of the glass panes are sealed and the enclosure is evacuated; the glass surfaces facing the enclosure are low-e coated to minimize the thermal radiation. Vacuum glazings have the advantage of lower weight and thinner thickness compared to the multilayered glazing solutions; hence, are promising for the refurbishment of today's double glazed windows. However, vacuum glazings have a large thermal bridge in the edge sealing, which can increase their *U*-values to ∼1 W/(m^2 K) [11]. The concept of triple vacuum glazing units with center *U*-values of about 0.2 W/(m^2 K) has also been proposed with four low-e coatings on the four glass surfaces within the two vacuum gaps [8], though no successful samples have been reported so far [11]. Aerogel glazing units (AGUs) with *U*-values of about 0.5–0.7 W/(m^2 K) have also been reported in the literature [17–20]. AGUs are architecturally similar to the double glazings, where the air cavity is filled with silica aerogel materials, which are a nanoporous material with low density (∼0.003–0.1 g/cm^3 depending on the porosity), low thermal conductivity (∼0.005–0.02 W/(m K) depending on preparation methods and measurement conditions, e.g. if evacuated or not), and good fire and acoustic resistance. Aerogels for glazing applications can be in forms of monolithic panes or granules; better optical and thermal insulation properties are usually achieved with monolithic aerogel panes [18,19]. However, the fact that aerogels are very fragile (i.e. typical flexural strength of 1 kPa to 1 MPa [21]) limits the application of monolithic aerogel panes for AGUs, e.g. the risk of failure under tensile/bending stresses due to wind load and/or external mechanical forces. In practice, AGUs are usually assembled with aerogel granules [22,23]; nevertheless, the loss of a clear view through the glazing aperture remains an obvious drawback. Table 1 compares the traditional double glazings with the recent window innovations. It is important to point out that, although IGUs with *U*-values of about 0.5–0.7 W/(m^2 K) have already been produced and sold commercially for a wide range of applications, e.g. for new buildings or building renovations [2,22–25], continued research, both fundamental and applied, will still be important and essential, e.g. to reduce the manufacture cost and to improve further the window performance [22,23,26].

Being an innovative glazing system, AGUs are of particular interest since their performance can be modified by, e.g. controlling the employed aerogel materials [17–20,29]. In other words, the factors that dominate the properties of aerogel materials will also affect the resulting AGUs, which actually open the possibility of designing high performance AGUs from the perspective of materials science. In this work, we have assembled light diffusing and thermally insulating AGUs by incorporating aerogel granules into the cavity of double glazings. Interesting enough, the experimental results indicate that the optical and thermal properties of AGUs are significantly affected by the particle size of the employed aerogel granules, of which the size effect seems analogous to those reported typically for nanostructured materials [30]. The fact that the particle size matters also with the durability of AGUs indicates further research efforts are necessary and important not only for the synthesis of aerogel materials with controlled sizes and properties, but also for the development of high performance AGUs for practical building applications.

2. Experimental

2.1. Materials and methods

Hydrophobic silica aerogel granules were received from PCAS, France, with typical particle sizes of about 3–5 mm (denoted hereafter as Aerogel-AB). Aerogel granules with smaller particle sizes (<0.5 mm, denoted hereafter as Aerogel-AS) were prepared by grinding and sieving the as-received PCAS aerogel granules. Fig. 1 shows the aerogel materials used in this work. Clear glass panels (350 mm × 500 mm × 4 mm) were cleaned with acetone and ethanol to remove the surface contaminations. Thermix® TX.N® plus spacer with gap size of 14 mm was used. Silicon sealant was purchased from Jula AS and used as received.

2.2. Assembly of glazing units

Fig. 2 illustrates the architecture of the glazing units in this work. The dimension of the glazing aperture is about 475 mm × 325 mm. The AGU sample WIN-AB contained aerogel granules with large particle sizes (i.e. Aerogel-AB, the as-received PCAS aerogel granules); the AGU sample WIN-AS was assembled by using aerogel granules with small particle sizes (i.e. Aerogel-AS). During the preparation, the glazing units were subjected to mechanical vibration to improve the packing of aerogel granules inside the cavity. A double glazing unit, WIN-ref, was also prepared for comparison purposes. The as-prepared glazing units were 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. Fig. 3 shows the assembled glazing units in this work. Small sized AGU samples (glazing area ∼4 cm^2) with different spacers (thickness 14–38 mm) were also prepared for optical measurement purpose.

2.3. Characterization

Optical properties of the aerogel glazing units were measured from 290 to 2500 nm on a Perkin Elmer Lambda 1050 UV/VIS/NIR spectrophotometer with a 150 mm Integrating Sphere Accessory, which operates in a reflection port close or open mode to measure the total or diffuse transmittance, respectively (Fig. 4). Solar radiation glazing factors of the obtained glazing units,

Table 1
A comparison between double glazing and recent window innovations.

	Structure[a]	U (W/(m^2 K))	T_{vis}[b]	T_{sol}[c]	SF[d]	References
Double glazings	G/A/LE/G	1.2	0.77	0.5	0.6	[27,28]
Triple glazings	G/A/LE/G/A/LE/G	0.5	0.66	0.37	0.5	[27,28]
Vacuum glazings	G/LE/V/G	1.5	0.75	0.60	0.74	[10]
Aerogel glazings	G/Aer/G	0.6	0.62	0.55	0.74	[20]
	G/Gran/G	1.0	0.29	0.29	0.36	[20]

[a] G: 4-mm float glass, A: 14-mm air cavity, LE: low-e coating, emissivity 0.07, V: 0.2-mm vacuum cavity, Aer: monolithic aerogel pane (14 mm in thickness), and Gran: aerogel granules (size: 0.5–3 mm).
[b] Visible solar transmittance.
[c] Solar transmittance.
[d] Solar factor, also denoted as *g*-factor and solar heat gain coefficient (SHGC) in literatures.