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Evacuated aerogel glazings

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Abstract

This paper describes the main characteristics of monolithic silica aerogel and its application in evacuated superinsulating aerogel glazing including the evacuation and assembling process. Furthermore, the energetic benefit of aerogel glazing is quantified. In evacuated aerogel glazing the space between the glass panes is filled with monolithic silica aerogel evacuated to a rough vacuum of approximately 1–10 hPa. The aerogel glazing does not depend on use of low emissive coatings that have the drawback of absorbing a relatively large part of the solar radiation that otherwise could reduce the space heating demand in residential buildings. The *U*-value of the glazing can be designed to meet the required value by increasing the monolithic silica aerogel thickness without the need for additional layers of glass. An aerogel glazing with 20 mm glass distance can reach a *U*-value below 0.5 W/(m^2 K) combined with a solar energy transmittance above 0.75.

Keywords: Superinsulating glazing; Monolithic silica aerogel; Evacuated glazing; High solar transmittance

1. Introduction

Windows in a building have a major influence on space heating demand and indoor environment both with respect to climate and daylight. Windows are still the thermally weakest part of the thermal envelope but on the other hand allow the use of solar heat and daylight. In the continuing effort to lower the heat loss from buildings window glazings have been significantly improved. The *U*-value has been reduced by the introduction of insulating gas fillings and almost invisible low-e coatings to reduce heat transfer by long-wave radiation. As an example, the *U*-value for a sealed double-layer glazing has been reduced from 3.0 W/(m^2 K) (12 mm air-filled enclosure) to 1.1 W/(m^2 K) (15 mm argon filling and 1 low-e coating). Further limited improvement can be achieved by the use of krypton filling. If the *U*-value should be further reduced an additional layer of glass and an additional low-e coating has to be applied. In this case the *U*-value can be lowered to approximately 0.5 W/(m^2 K). However, both the additional layer of glass and the additional low-e coating also reduces the solar gain and the daylight transmittance. Furthermore, the additional layer of glass increases the weight of the glazing by 33% and requires stronger window frames than those used for double-glazed solutions. Fig. 1 shows the approximate relationship between glazing *U*-value and total solar energy transmittance (*g*-value) for typical sealed glazing units on the market excl. solar control glazing. Furthermore Fig. 1 shows the combined influence of *U*- and *g*-value on the energy balance for a typical single-family house summed over the heating season (approximately October–April) in a Danish climate [1]. The diagram in Fig. 1 shows that the benefit of adding a third or fourth layer of glass is limited due to the decrease in *g*-value. As an example, a standard double-layered glazing with one low-e coated surface and argon filling (*U*-value = 1.2 W/(m^2 K), *g*-value = 0.63) results in an average net energy balance of 15 kW h/m^2 glazing. If a triple glazed solution with two low-e coated surfaces and two argon filled enclosures (*U*-value = 0.6 W/(m^2 K), *g*-value = 0.46) is chosen, the net average energy balance increases to 35 kW h/m^2). In the search for further energetic improvement of window glazing especially two different advanced glazing solutions have been investigated, i.e. vacuum glazing and the evacuated aerogel glazing.

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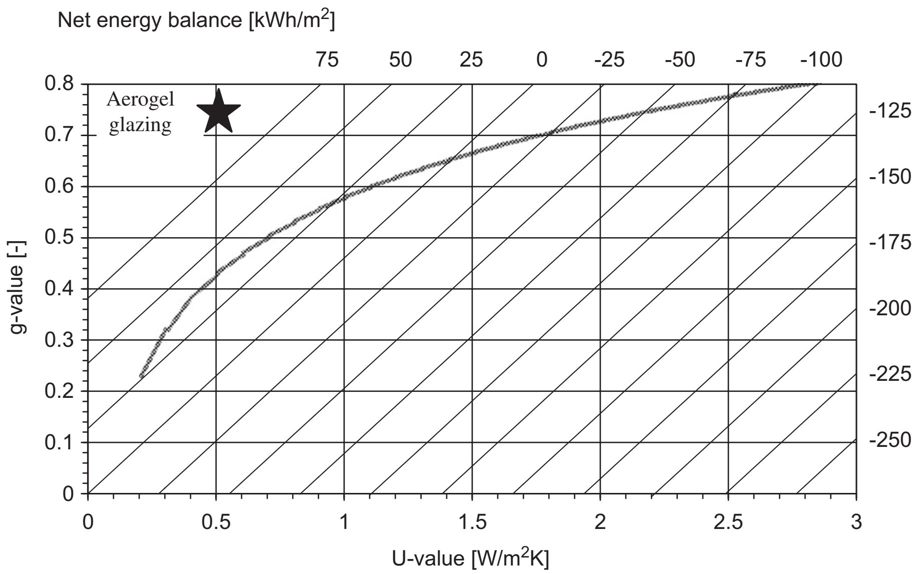

Fig. 1. Energy balance (kW h/m^2) for window glazing as function of U-and g-value (straight lines). The bold curve represents the typical relation between U-and g-value for window glazing systems. The position of the aerogel glazing in the diagram is marked with a star.

Vacuum glazing consists of two sheets of glass with a distance of approximately 0.5 mm [2,3]. The glazing is sealed at the edges and the space between the glass panes are evacuated to a fine vacuum in the range of 10^{-4} hPa. The glass panes are kept apart by means of regular distributed small pillars. Both the glass surfaces facing the enclosure are low-e coated to reduce thermal radiation between the glass panes to a minimum. The U-value of vacuum glazing is in the same range as that of triple-glazed sealed glazing units with argon filling, but has the advantage of lower weight and the slimness that makes vacuum glazing feasible as a replacement for single glazing. The drawback is the large thermal bridge in the edge sealing as it has to be completely airtight and has a thickness of only approximately 0.5 mm. The evacuated aerogel glazing is a double-pane sealed glazing unit, where traditional gas filling is replaced by monolithic silica aerogel (hereafter just called aerogel), which is a highly porous and transparent material with pore sizes in the range 10–100 nm. The small pore size makes it possible to achieve an apparent thermal conductivity below 0.010 W/(m K) combined with a solar energy and daylight transmittance of approximately 90% for a material thickness of 20 mm. These two characteristics make the monolithic silica aerogel very interesting for superinsulating window glazing units [4].

2. Monolithic silica aerogel

Aerogels were first made by Kistler in the early 1930s [5]. The initial time consuming process was improved by developing a procedure where alcogels directly prepared from alcoxides were supercritically dried from ethanol or methanol [6,7]. Due to the high supercritical temperature of alcohols, a new and safer route consisting of an exchange of the pore liquid with CO_2 followed by a drying at the supercritical conditions of CO_2 was developed [8]. Later, direct supercritical CO_2 washing was tested to improve the diffusion in the nanoporosity of the wet gel [9]. Since then, few studies had been performed in the aerogel field with such an innovative process [10]. However, production of large scale aerogel tiles were first made when using direct supercritical CO_2 drying combined with a patented gel preparation [11] and a wet gel-strengthening step [12]. The large-scale production technique was developed and established in two European-financed research projects [13,14]. Within these projects it succeeded in transferring the lab scale results to a pilot-scale production plant at the Swedish company, Airglass AB. The pilot-scale production process was developed to have a large degree of recycling, especially of CO_2. Another very important development was the production of aerogel tiles with completely parallel surfaces—a must for use in aerogel glazing production. The maximum aerogel tile size is $0.58 \times 0.58\,m^2$, only limited by the size of the autoclave. In principle the thickness can be varied freely—in the actual projects it was 15 mm. The resulting monolithic silica aerogel is a highly porous material with a skeleton of 99.9% SiO_2 and a porosity of 90% with pore sizes in the range 10–100 nm. The density is in the range 140–150 kg/m^3. The nanoscaled pore sizes results in a thermal conductivity of 0.017 W/(m K) at atmospheric pressure. This is lower than that for still atmospheric air (0.026 W/(m K)). The thermal conductivity can be further reduced to approximately 0.010 W/(m K) by evacuation of the aerogel to a rough vacuum in the range 10–50 hPa, in which case the thermal conductivity in the pore gas is essentially eliminated. The measured daylight and solar energy transmittance is approximately 90% for 15 mm aerogel thickness corresponding to a calculated extinction coefficient of 8–9 m^{-1}.

3. Aerogel glazing assembly

The low ultimate tensile strength of monolithic silica aerogel requires the aerogel to be protected against mechanical impact and free water as the surface tension of water will destroy the aerogel pore structure. Furthermore, the wish for evacuation of the aerogel also calls for an envelope surrounding the aerogel. This is achieved by placing the aerogel in between two layers of glass and sealing the sandwich of glass and aerogel at the edges. The evacuation of the glazing eliminates the risk of tensile stress in the aerogel for example due to wind load and temperature difference across the glazing because the atmospheric pressure is working on all surfaces of the glazing.

3.1. Low conductive and airtight edge sealing

The edge sealing is the most critical part of the glazing as it has to be airtight and also has to have a very low thermal conductivity in order not to ruin the otherwise superior thermal performance of the glazing. In general only glass and metals are completely airtight but they are both characterised by a high thermal conductivity relative to the evacuated silica aerogel. Therefore, a laminate-Mylar® 250 RSBL300 from DuPont [15] developed for the vacuum insulation panel technology is used as the almost air and vapour tight barrier in the edge sealing. The laminate is not 100% tight, but as only a rough vacuum is required a limited pressure increase during the lifetime of 25–30 years of the glazing is allowed. The laminate is sealed to the glass covers by means of a compressed butyl sealant supported by a polystyrene spacer profile that also protects the laminate (Fig. 2). Due to the rough vacuum inside the glazing there is no need for a secondary sealant, e.g. the polysulphide sealant in traditional sealed glazing units required to make a firm connection between the two glass panes. The atmospheric pressure ensures a permanent fixation of the glass panes to the aerogel and polystyrene spacer. Upon a loss of vacuum the glazing will not fall apart as the butyl sealant will keep the panes in place for a reasonable period of time.

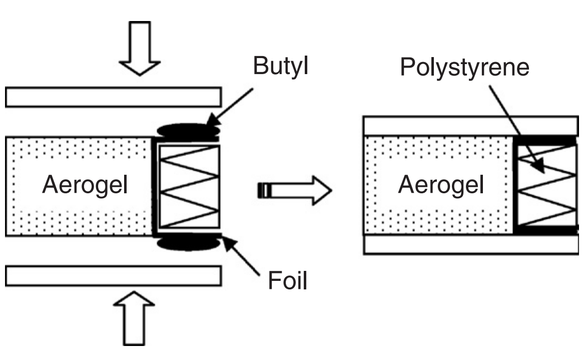

Fig. 2. Cross section of the rim seal solution used for the evacuated aerogel glazing. The arrows in the left part of the figure indicates that the glass panes are pressed against the rim seal and butyl strips.

The overall glazing U-value including the thermal bridge in the edge sealing was calculated to be $0.46\,\mathrm{W/(m^2\,K)}$ for a $0.55 \times 0.55\,\mathrm{m}^2$ glazing with a centre U-value of $0.42\,\mathrm{W/(m^2\,K)}$. This corresponds to a linear thermal transmittance coefficient of $0.020\,\mathrm{W/(m\,K)}$.

3.2. Evacuation of the aerogel glazing

The way the aerogel glazing is evacuated has a significant influence on the way the glazing is assembled and vice versa. Two principal routes could be followed: (1) evacuation after assembling or (2) assembling in a vacuum chamber.

Evacuation after assembling makes the assembling fast but requires a large storage, where the glazings are connected to the evacuation equipment until evacuated. It further implies that e.g., a pipe stub is integrated in the edge sealing leading to increased risk of leakage. Assembling in a vacuum chamber means that the assembling process will take a longer time for each glazing, but when the glazing leaves the vacuum chamber it is ready for use. Beside no penetration of the edge sealing is required. The determining parameter for which of the two evacuation routes to follow is the evacuation time in each case. The highly porous monolithic silica aerogel with pore sizes in the nanoscale has a diffusion coefficient in the range 10^{-5}–$10^{-6}\,\mathrm{m^2/s}$ [16,17] which makes the diffusion in the aerogel the governing parameter with respect to evacuation time. Rough calculations of the internal pressure evolution in the aerogel during evacuation have been carried out by means of a simulation tool for calculation of the three-dimensional temperature distributions and the analogy between heat flow and molecular Knudsen flow in a porous material (Table 1). Fig. 3 shows the calculated average pressure inside a $0.55 \times 0.55\,\mathrm{m}^2$ glazing with an aerogel thickness of 20 mm for 3 different cases: (1) evacuation at a midpoint of one of the edges, (2) evacuation over the total edge area and (3) evacuation over the top surface area. Evacuation through a pipe with a cross sectional area of

Table 1
Analogy between heat flux and molar flux in a highly porous material where Knudsen flow is dominant

Heat flux	*Molar flux*
$\dot{Q} = \lambda \times A \times \frac{dT}{dx}$	$\dot{n} = \left(\frac{D}{R \times T}\right) \times A \times \frac{dP}{dx}$
Heat capacity	*Molar capacity*
$\dot{Q} = V \times (\rho \times C_p) \times \frac{dT}{dt}$	$\dot{n} = V \times \left(\frac{1}{R \times T}\right) \times \frac{dP}{dt}$
$\dot{Q}$: heat flux (J/s = W)	$\dot{n}$: molar flux (mol/s)
λ: thermal conductivity (W/mK)	D: diffusion coefficient (m^2/s)
A: area (m^2)	R: gas constant (J/mol K)
T: temperature (K)	T: temperature (K)
x: distance (m)	A: area (m^2)
t: time (s)	P: pressure (Pa)
V: volume (m^3)	x: distance (m)
ρ: density (kg/m^3)	V: volume (m^3)
C_p: heat capacity (J/kg K)	t: time (s)

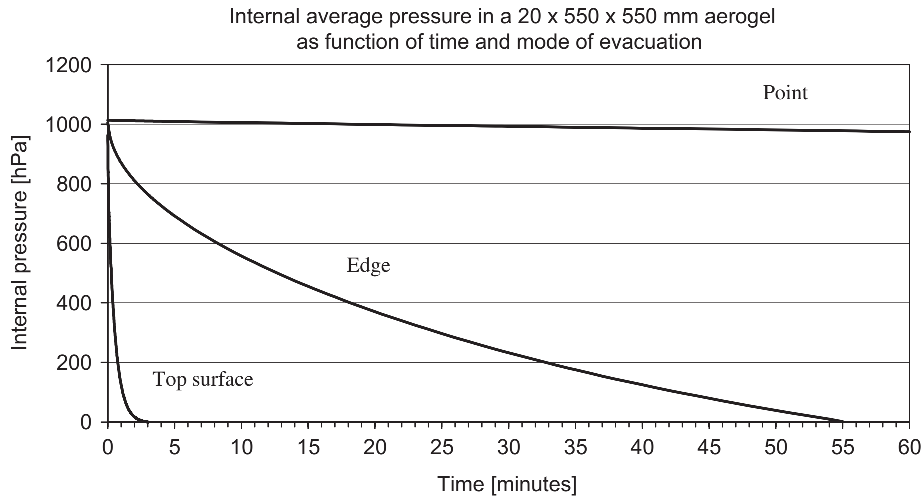

Fig. 3. Internal average pressure in a $20 \times 550 \times 550\,\text{mm}^3$ aerogel as function of time and evacuation mode.

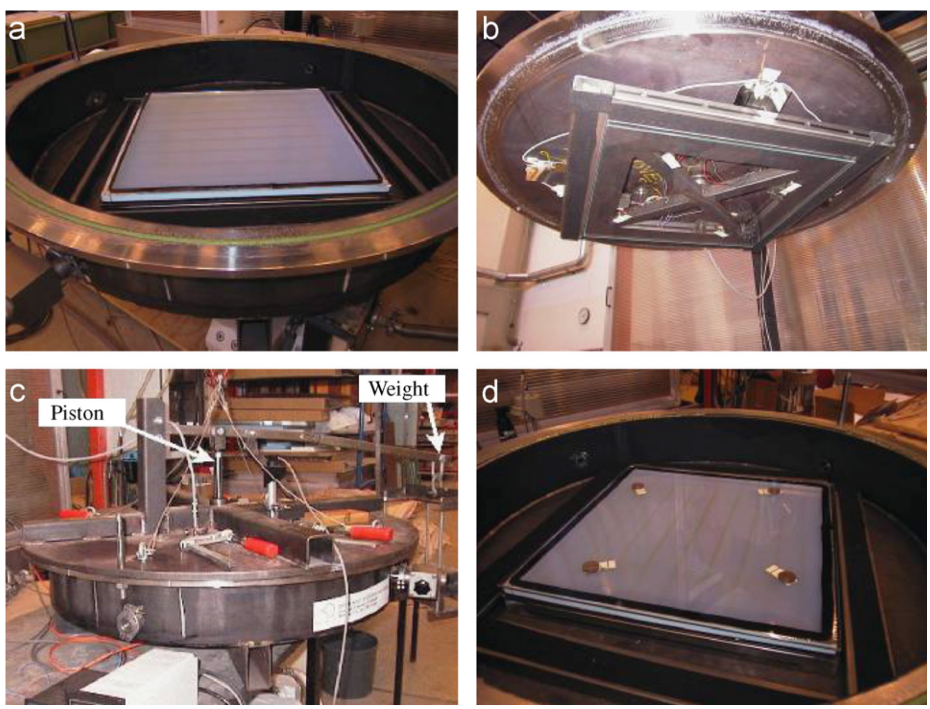

Fig. 4. Pictures showing the main steps in aerogel glazing assembling and evacuation in a vacuum chamber. (a) The aerogel is positioned on the lower glass pane and the rim seal is applied around it. (b) The upper glass pane is held by electromagnets in the lid. (c) The evacuation takes place and after 10 min the upper glass is lowered via the piston and pressed against the aerogel and rim seal. (d) The final glazing–metal disks are still fixed to the upper glass.

$200\,\text{mm}^2$ (the upper curve in Fig. 3) results in a calculated evacuation time of 6 days to reach the required internal pressure below 10 hPa. Evacuation through the edges lowers the evacuation time to 1 h, while evacuation over the top surface only requires approximately 3 min depending on the aerogel thickness and not on the aerogel volume. Based on the investigation of evacuation time and the risk of leakages by integration of a pipe in the barrier material the assembling in a vacuum chamber is chosen. An aerogel glazing evacuation apparatus (AGEA) [18] was used for assembling of laboratory-scale prototypes with a maximum size of $0.55 \times 0.55\,\text{m}^2$. The assembly process includes the following steps (Fig. 4).

- The lower glass with the aerogel and rim seal is positioned in the vacuum chamber (Fig. 4a) and the upper glass is fixed to a frame in the lid of the vacuum chamber by electromagnets working on small metal disks glued to the glass pane (Fig. 4b).
- The lid is closed in which position the upper glass is held at a distance of a few centimetres above the aerogel and the evacuation begins (Fig. 4c).

- After approximately 10 min of evacuation the frame in the vacuum chamber holding the upper glass pane is lowered and firmly pressed against the aerogel and the rim seal by means of a piston and weights (Fig. 4c).
- The vacuum chamber is gently vented and the atmospheric pressure now working on the glazing surfaces increases the pressure on the butyl sealing strips and results in a complete sealing between the laminate and the glass panes.
- The electromagnets are switched off and the vacuum chamber is opened. Fig. 4d shows the final glazing with the metal disk still fixed to the upper glass pane.

4. Energetic performance

4.1. Measured U- and g-value

Several aerogel glazing samples have been made within the EU financed project HILIT+ [14] following the route described above. The aerogel tiles produced at Airglass AB measure approximately $0.58 \times 0.58 \times 0.015\,m^3$. Due to uneven shrinkage during the drying process the edges are not always perfect and the aerogel tiles are cut by a band saw to the final size of $0.55 \times 0.55 \times 0.015\,m^3$. The thickness of 15 mm is determined by the moulds at Airglass, but producing aerogel in 20 mm thickness is not considered a problem. During ventilation of the pressure chamber the aerogel is slightly compressed to a final thickness of 13.5 mm.The thermal conductivity is in the range 0.010 W/(m K) at a pressure of 10 hPa, which leads to a calculated centre heat loss coefficient for the glazing of approximately $0.66\,W/(m^2\,K)$. Low iron glass panes (SSG Diamond from Saint-Gobain Glass) with a thickness of 4 mm are used for the glazing prototypes. The glasses have antireflection coatings provided by a surface etching process commercialised by the Danish company SUNARC A/S [19]. This process is widely used for thermal solar collector covers and glass for PV modules. The low iron content reduces the absorption of solar radiation in the glasses from approximately 10% to 1%. The anti-reflection treatment reduces the losses due to reflection from 8% to 3%.

A guarded hot plate apparatus (single plate) has been used for measurement of the aerogel glazing U-value. A constant electrical power is supplied in the metering area of $0.15 \times 0.15\,m^2$. The metering area is in close contact with one side of the glazing and the power is adjusted until a glazing surface temperature of approximately 10 K above the surrounding room temperature is achieved. The metering area is surrounded by a 0.10 m wide guard area controlled to have a temperature identical to the metering section. Also a guard on the back of the metering section and the guard area is controlled to have the same temperature as the metering section and the guard area. In this case, all heat losses from the metering section take place only through the glazing. A water-cooled cold plate is positioned on the other side of the glazing opposite the metering and guard sections. The temperature is controlled to approximately 10 K below the surrounding room temperature. The chosen temperature levels ensure that the average temperature of the glazing is equal to the surrounding room temperature minimising the measurement error due to multidimensional heat flows. The temperature difference across the glazing is measured by two calibrated thermocouples and the U-value is calculated from the applied power, the metering section area and the measured temperature difference. The U-value of the produced aerogel glazing prototypes has been measured to $0.66 \pm 0.03\,W/(m^2\,K)$, which corresponds very well to the expectations. The solar energy transmittance has been measured both in the laboratory and outdoors on a bright sunny day. The laboratory measurements have been carried out as part of the European project [14] at Institut für Solar Energie at the Fraunhofer Intitute in Freiburg, Germany by means of a large (60 cm diameter) integrating sphere. The outdoor measurements are carried out by placing the glazing on a supporting frame adjusted to obtain normal radiation on the glazing. The transmitted solar radiation is measured by a Kipp and Zonen CM11 pyranometer placed just below the glazing and shielded against reflected radiation from the surroundings. The solar radiation is measured before and after the measurement of the transmitted solar radiation and averaged. The transmittance is calculated as the transmitted solar radiation relative to the average of the solar radiation measured before and after. Both the laboratory and the outdoor measurements showed a normal to hemispherical transmittance of 75–76%. The total solar energy transmittance which includes the effect of the absorbed solar energy in the inner glass and the inner part of the aerogel, and which the room behind benefits from, will be approximately a few percentage points higher.

4.2. Calculated influence on space heating demand

Even though the optical quality of aerogel glazings is not yet at a level where they can replace existing sealed glazing units (see Section 5) aerogel glazings could be used in a very large part of the glazed area in a typical single family house, where the visual quality is less important e.g. roof-, bathroom-, bedroom-windows, etc. Therefore, as an upper estimate, the calculated influence on the space heating demand has been carried out for a typical single-family house in a Danish climate. The calculations for the aerogel glazing case is carried out assuming an aerogel glazing with 20 mm aerogel thickness resulting in a centre U-value of $0.5\,W/(m^2\,K)$ and a total solar energy transmittance (g-value) of 0.75. The high solar energy transmittance combined with the low U-value makes the aerogel glazing superior to all other glazing solutions for residential buildings. The energetic impact on the energy consumption for space heating has been evaluated through simulations of annual energy consumption for a typical single-family house in Denmark with triple glazed argon-filled glazing

Table 2
Calculated energy consumption for space heating in two houses insulated according to the Danish building code and to the passive house, respectively, with either argon-filled triple-glazing (U-value = 0.6 W/(m^2 K), g-value = 0.46) or with evacuated aerogel glazing (U-value = 0.5 W/(m^2 K), g-value = 0.75)

Building insulation level	Space heating demand (kW h/year)	
	Triple glazing	Aerogel glazing
Building code	6220	5040
Passive house	2070	1380

(U-value = 0.6 W/(m^2 K), g-value = 0.46) and with evacuated aerogel glazing, respectively. The total area of the house is 135 m^2 and the total transparent area of windows and doors are 29 m^2 distributed with 8 m^2 facing east, 7 m^2 facing south, 10 m^2 facing west and 4 m^2 facing north. Two cases have been investigated: (1) a house insulated according to the Danish building code and (2) a house insulated to the passive house standard (space heating demand < 15 kW h/m^2/year). The results are shown in Table 2. The results in Table 2 shows an energy saving of 1180 kW h/year (19%) by exchanging triple-layered argon-filled glazing with aerogel glazing in a typical new built single family house in Denmark. In a low-energy house the savings are 700 kW h/year, which correspond to 34% decrease in space heating demand. The use of aerogel glazing has to be carefully analysed during the design process and might be combined with efficient ways to prevent overheating, e.g. automatic venting, solar shading devices etc.

5. Visual performance

The developed method of producing the aerogel tiles with parallel and smooth surfaces results in an undistorted view through (Fig. 5). However, there is still some haze due to scattering in the aerogel. The scattering is most visible if the aerogel glazing is exposed to direct sunlight, in which case the strong diffusion of the light makes the glazing almost impossible to look through. This makes the present quality of aerogel most suitable for north facing windows (Fig. 5) and for daylight components in general.

The north facing window solution is especially interesting, as the aerogel glazing, even in this position, has a positive energy balance seen over the heating season in a Danish climate. And from a daylight point of view the north facing position results in a pleasant soft daylight which, with aerogel glazing, can be achieved even with net energy gains.

A special consequence of the evacuated aerogel glazing with perfect parallel surfaces is that the parallelism will be unaffected by changes in temperature, and by then also the reflectance of images in the glazing of, e.g., neighbour buildings. This avoids the so-called Dallas effect where the

Fig. 5. Example of an evacuated aerogel glazing in a well-insulated frame. The view through shows no distortion of the image but a slightly haziness can be observed. The picture is taken viewing north without direct sunlight hitting the glazing.

mirrored images in large glass facades changes and become distorted due to pressure changes in the gas-filled glazings.

6. Conclusion

Thanks to the research carried out as part of two European funded research projects, the quality of monolithic silica aerogel with respect to visual quality has reached a level that makes it suitable for use in evacuated aerogel glazing solutions not exposed to direct solar radiation or for daylight components. A process for making of 0.58×0.58 m^2 monolithic crack-free aerogel tiles with a thickness of 15 mm has been developed within the European project and it is implemented at the pilot plant at Airglass AB in Sweden—the size of the aerogel tiles is determined by the size of the autoclave.

The monolithic silica aerogel has a solar energy and daylight transmittance of approximately 90% combined with a thermal conductivity of 0.017 W/(m K) at atmospheric pressure. If evacuated to a rough vacuum below 10–50 hPa a thermal conductivity below 0.010 W/(m K) can be achieved. The low thermal conductivity, the high solar energy transmittance and the good optical quality makes monolithic silica aerogel very attractive for use in super-insulating window glazing. Prototypes of evacuated aerogel glazing have been assembled in a vacuum chamber. The evacuation time is approximately 10 min including the pumpdown time of the vacuum chamber. A special rim seal with very low thermal conductance has been developed based on laminated plastic foils developed for vacuum insulation panels. The glazing prototypes have a measured U-value of 0.66 W/(m^2 K) and a total solar energy transmittance of 76–80% making it the best known glazing solution with respect to the net energy balance. The annual energy saving for a typical Danish single-family house built according to the present building code is approximately 1200 kW h/year corresponding to 19% if triple-layered argon-filled glazing with two low-e coatings are exchanged with evacuated aerogel glazing. In a low-energy house, the energy savings will be approximately 700 kW h/ year corresponding to 34% of annual space-heating demand.

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