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Application of super-insulating translucent silica aerogel glazing system on commercial building envelope of humid subtropical climates - Impact on space cooling load

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Abstract: Solar radiation through the glazing area is the main source of space cooling load in cooling-dominant climates. Application of energy-efficient glazing system can significantly reduce the energy consumption of air-conditioning systems in summer, thus attracts much attention. In this paper, a super-insulating glazing system which is formed by two layers of conventional clear single glass panes and a layer of silica aerogel filled in between is studied. Several glazing samples were prepared and the thermal and optical parameters were measured, and the annual energy performance was also simulated. The result indicated that in a typical commercial building in Hong Kong, the application of silica aerogel window system can reduce the envelope heat gain by more than 60%. It was also found that if the internal heat source in a building takes a small proportion in the total space cooling load, the performance of silica aerogel window will be better.

Keywords: solar heat gain, commercial building envelope, silica aerogel, energy-efficient glazing system, space cooling load

Introduction

Windows play an important role in providing the occupant with thermal and visual comfort and are considered to be the most important part of a building envelope. According to our previous study, solar heat gain through window area accounts for 65%~80% of the cooling load caused by building envelope in cooling-dominant climates [1]. Thermal insulation on window area is among the top topic in building energy research.

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Recently, a new insulation idea on building named “transparent insulation” has attracted much attention. The fundamental of transparent insulation is to apply opaque insulation material directly on glazing surface, trying to reduce the heat transfer through the glazing area while obtain a proper level of daylighting. At present, transparent insulation is mainly applied in cold climates where heating is necessary in winter. Multiple-layer glazing and low-e glass are the most popular transparent insulation technologies. There have been many literatures discussing the thermal performance of multiple-layer glazing and low-e glass and factors that may affect their performance, such as the air layer thickness, the glass pane thickness and the sealing of glazing systems [2, 3, 4].

Aerogel is a porous material which was first created by Kistler in 1931 [5]. Silica aerogel is the most common type of aerogel, and thus drawn much attentions [6, 7]. Aerogel has a very large porosity and a very small cavity size, which causes the thermal conductivity of aerogel to be even smaller than the gas it contains. Due to its unique physical properties, aerogel has been noticed by professionals since then. Researchers introduced in many theoretical models trying to describe and predict heat transfer process within the aerogel structure. Zhao et al. developed a combined radiation and conduction model using modified anomalous diffraction theory to simulate the radiative and heat transfer characteristics of fiber-loaded silica aerogel thermal insulation materials. They claimed that the total conductivity of the sample can be reduced by reducing the fiber length-to-diameter ratio. They also claimed that 4-6 micron meter diameter aerogel fibers performed best for high temperature insulation [8]. Xie et al. also proposed a theoretical model to calculate the total thermal conductivity of silica aerogel insulating material. Their model can be described as a fractal-intersecting sphere model and the scale effect on gas conduction and solid-matrix conduction were considered in the model. They discovered that temperature and the fiber diameter can significantly affect the thermal performance [9]. Later, they presented an experiment study on the performance of silica aerogel material in high temperature. With the experiment result, they proposed a heat transfer model in which the endothermic reaction is considered [10]. Yu et al. developed a realistic microstructure radiative transfer theoretical model to analysis the radiative heat transfer of silica aerogel. The theoretical prediction arising from the model was compared with experiment data and a good agreement was achieved [11]. Wei et al. measured the thermal conductivity of silica aerogel insulating material from 300 to 970 K and from 0.045 Pa to atmospheric pressure with the transient hot-strip (THS) method. They also developed a theoretical model based on unit cell method. Comparing the model result with the experiment data, they found that the model and experiment matched well [12]. Later, Wei et al. conducted a test on the radiative thermal transfer of silica aerogel and its composite insulation materials with a Fourier transform infrared spectrometer. During the measurement infrared wavelengths ranging from 2.5 to 25 micron meter was considered. The result indicated that the radiative conductivity of tested sample showed strong dependence on the wavelength, and was almost proportional to the cube of temperature, decreasing as density increases [13]. Bi et al. proposed a modified 3-D numerical model for the prediction of effective thermal conductivity of aerogel, and did a validation with existing experiment data and theoretical couple model. They discovered that the effective thermal conductivity of silica aerogel is insensitive to the geometry structure, thus simple structure can be applied in analysis [14].

Aerogel was first introduced in building construction as an insulating materials applied for wall and roof surface. Stahl et al. developed and tested an aerogel based insulation rendering which they claimed could be applied on both interior and external building surface [15]. Yuan et al. developed a method of improving the strength and thermal insulation property of silica aerogel fiber composites by adding TiO2 powder at high temperature. They also tested the optimal forming pressure for the heat insulation property [16]. Dowson et al. studied the possibility of replacing the conventional glass cover on the flat plate solar air collectors with lightweight polycarbonate panels filled with aerogel. After a 7 days test period in UK, they reported a 118 to 166 kWh/m2/year output could be achieved, compared with the 110 kWh/m2/year output on a conventional single glazed collectors and 140 kWh/m2/year output on a double glazed collector [17]. Chen et al. developed an aerogel-filled sandwich panel insulation material, aiming at providing both mechanical support and extra insulation at the same time. They conducted mechanical and thermal tests on the panels they produced and claimed that the insulation panel can be considered as a competitive building insulation material [18]. Cuce et al. did a study on the optimum aerogel insulation thickness under local energy cost and energy sources in Nottingham, UK. They discovered that the optimum aerogel insulation thickness varied from 22-62mm compared with 45-165mm while conventional insulation materials were applied [19].

From above literatures it is obvious that at first, the majority of researchers and engineers just considered aerogel as an alternative for conventional surface insulating materials. The transparent feature of aerogel material was often ignored. Actually, in the 1980s, some researchers had considered silica aerogel as a potential transparent insulation material which may be applied in super insulation windows. As early as 1986, Caps and Fricke had tested the infrared radiative heat transfer of transparent silica aerogel. Though the measurement was done quite roughly, they managed to get a mean radiative conductivity of around 0.002W/mK [20]. The next year, they also investigated the impact of surface emissivity, density, internal gas pressure and external load on the spacers on the thermal performance of silica aerogel materials [21]. In the year 1993, Platzer and Bergkvist had studied the structural properties of transparent aerogel materials using elastic lighting scattering [22]. In the year 1998, Technical University of Demark started to consider the practicability of silica aerogel glazing application, Duer and Svendsen prepared several aerogel glazing samples, trying to find the optimum edge seal technique [23]. Table 1 summaries the research conducted on the development of highly insulating aerogel glazing system all around the world in the last decade:

Table 1 Summary of worldwide research on silica aerogel glazing

Authors	Institutions	Research activities
K. I. Jensen, J. M. Schultz, F. H. Kristiansen	• Technical University of Denmark, Demark	• Development of a monolithic silica aerogel transparent glazing, and received a less than 0.7 W/m2K heat-loss coefficient and a 76% solar transmittance in the center of the 15mm thick aerogel layer [24, 25]. • Calculation analysis trying to quantify the energy performance of silica aerogel glazing and claimed that in a typical Danish single family house, replacing conventional glazing with silica aerogel glazing can achieve an annual reduction of 1200 kWh, which is 19% of annual heating demand [26].
M. Reim, A. Beck, W. Korner, R. Petrickvic, M. Glora, M. Weth, T. Schliermann, J. Fricke, CH. Schmidt, F. J. Potter, J. Manara, S. Korder, M. Arduini-Schuster, H. P. Ebert	• Bavarian Center for Applied Energy Research, Germany • Glaswerke Arnold Gmbh and Co KG, Germany • Cabot GmbH, CAB-O-SIL Division, Germany	• Conducted a thermal performance tests on self-developed aerogel glazing, and claimed that their less than 50mm thick glazing sample can achieve a solar energy transmittance of 35% [27]. • Prepared a series of aerogel samples and conducted a completed optical and thermal test [28].
C. Buratti, E. Moretti	• Department of Industrial Engineering, University of Perugia, Italy	• Prepared several sandwich-type aerogel glazing samples with different thicknesses and conducted a test on the thermal and acoustic performance [29, 30].

From the above summary, it can be concluded that though there have been several literatures discussing the application of silica aerogel glazing system, only three research groups all around the world were involved. All these three groups were located in Europe, where the latitude is high, and heating is necessary in winter. In Europe, heat loss during heating season is considered the major issue on building envelope design, because the temperature difference during heating season is way larger than that during cooling season. While in cooling-dominant climates like Hong Kong, reducing space cooling load by cutting down heat gain through envelope is the major concern.

However, at present no literatures were found focusing on the application of silica aerogel glazing in cooling-dominant climates.

This paper presents a study on the application of silica aerogel window system on commercial building envelope in cooling-dominant climates like Hong Kong. First, a silica aerogel window sample was manufactured. The optical and thermal features of the window sample were then tested. A typical commercial building model was then constructed. The annual energy performance of silica aerogel glazing system was then simulated based on the test data in EnergyPlus. A comparison of silica aerogel glazing and low-E glazing was also conducted.

Methodology

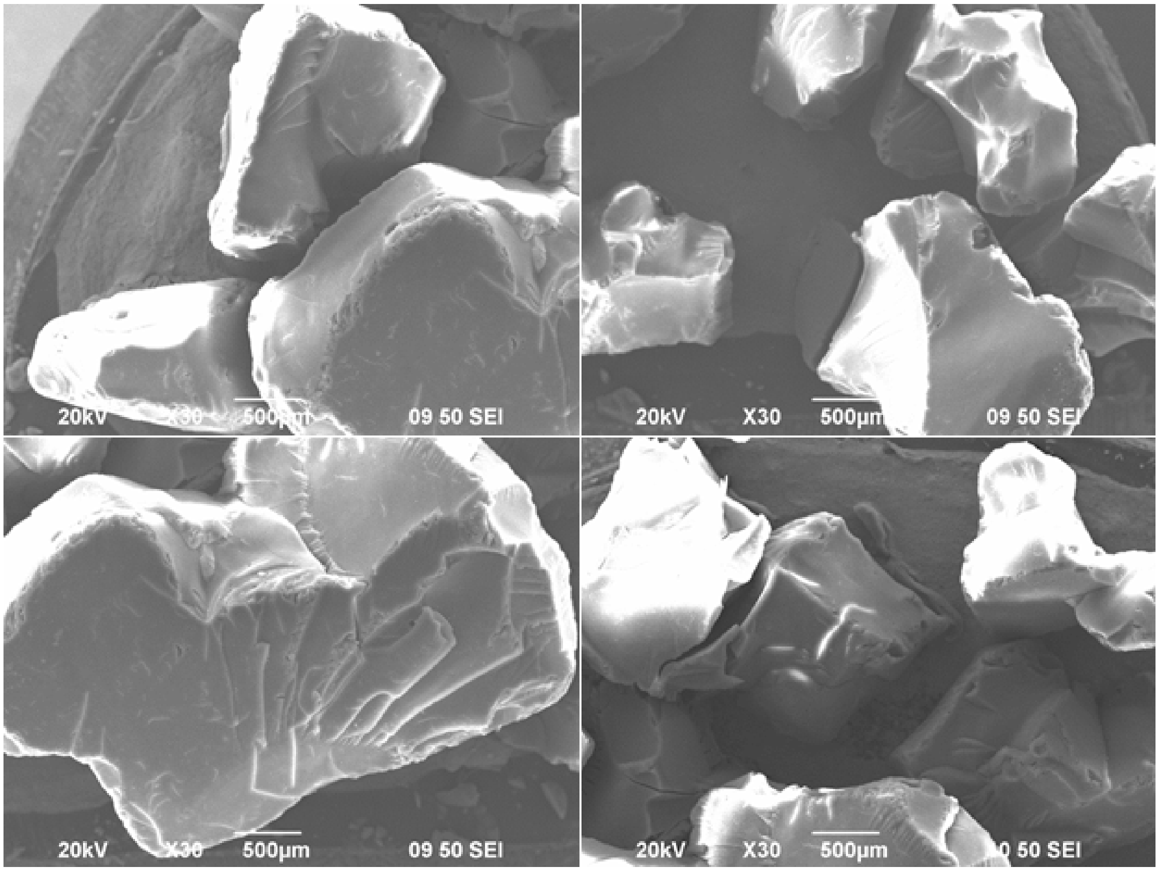
1. Preparation of silica aerogel window sample

The silica aerogel material used in the window sample was supplied by the Cabot Corporation. Table 2 gives the features of the silica aerogel product. Figure 1 presents the appearance of the product under naked-eye and scanning electron microscope.

Table 2 Product features of the silica aerogel material

Particle size range	0.7-4.0mm
Pore diameter	~ 20nm
Porosity	>90%
Particle density	120-180kg/m3
Bulk density	65-85 kg/m3
Surface area	600 - 800m2/g

A. Naked-Eye



B. Scanning Electron Microscope

Figure 1 Appearance of the silica aerogel product

The silica aerogel glazing system is a sandwich-type window with two layers of 6mm thick clear single glass with the aerogel product filled in between, as shown in Figure 2. Considering the aerogel filling cannot receive any pressure from the single glass layer, the edge sealing is the most challenge part. It should be strong enough to hold the single glass, it should be airtight. At the same time it should possess a low thermal conductivity, so that the thermal performance of the whole window system would not be ruined. Of the three groups that have produced silica aerogel windows samples, Jensen et al. and Reim et al. have introduced their sealing methods in detail. The silica aerogel material Jensen et al. applied was evacuated to 1-10 hPa, and the material was monolithic. They did not have to pay much attention on the strength of the supporter. So they selected a Polystyrene supporter [26]. Reim et al. used a double-skin sheet filled with silica aerogel grains as the insulating part [27]. Referring to the sealing process of Jensen et al. and Reim et al., we decided to use a surrounding support sealing instead of crossing support sealing. Figure 3 gives the schematic diagram of the edge sealing. The single glass cover is supported by an aluminum bracket. Pressed polystyrene is applied on the bracket sealed surfaces with sealant. The outer edge is then covered with aluminum window frame. After the complete package, the window sample is ready for parameter test. The appearance of the packaged silica aerogel window sample is displayed in Figure 4 below.

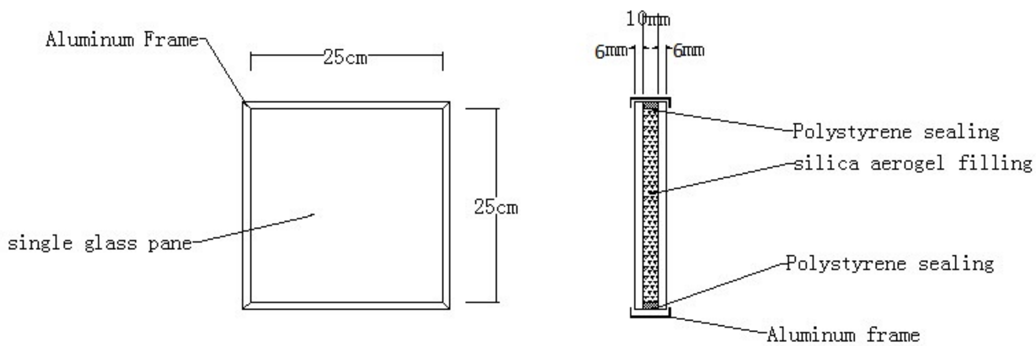


Figure 2 Diagrammatic sketch of the silica aerogel window sample

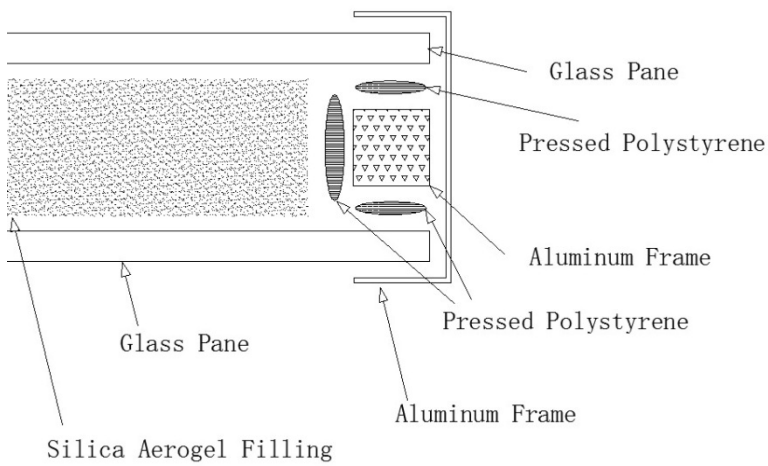


Figure 3 Schematic diagram of the edge sealing

Figure 5 Appearance of the silica aerogel window sample

2. Simulation set up

Once the thermal and optical parameters of the window sample are obtained, simulation tools can be utilized to predict the energy performance of the silica aerogel window. in the simulation study, a world-famous building energy simulation program EnergyPlus is applied. Based on state-space techniques, EnergyPlus is able to calculate the space load required to maintain a set condition through some sort of HVAC system. Many previous studies have proved its accuracy and adaptability [31, 32, 33].

A typical commercial building model was constructed for the annual energy simulation. The model was constructed strictly according to the reference building construction in the official guideline of Hong Kong Government [34]. The appearance of the model building is shown in Figure 5 (the arrow in the figure stands for north orientation). The building has one basement floor and 27 above ground floors. The first three floors were used for shopping mall. The 4th and 5th floors were car park. The rest floors were used as offices. Only the office and shopping mall area was air-conditioned. The schedules of occupant, lighting, equipment as well as air-conditioning were defined strictly according to the design guideline of Hong Kong Government [35]. Other widely used parameters applied in the simulation are listed in Table 3. During the simulation, the indoor temperature set point was 25℃. The simulation time step is 10 minutes. The detailed building envelope data was listed in Table 4.

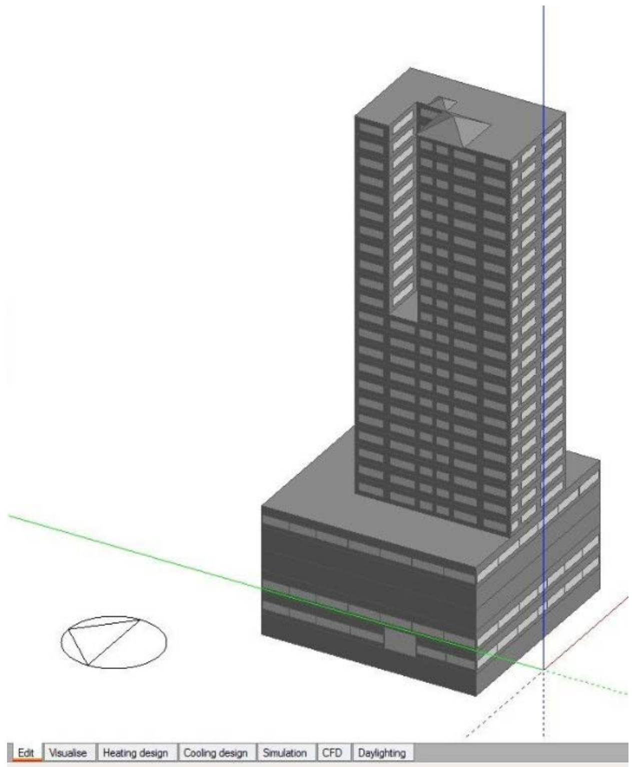


Figure 5 Appearance of the model building

Table 3 Parameters setting during simulation

A. Density of interior heat source

Floor type	Occupant density (m^2/person)	Minimum fresh air supply (L/s/person)	Lighting (W/m^2)	Electrical equipment (W/m^2)
Office	13	8	15	10
Shopping mall	10	10	23	10

B. Structure parameters

Floor type	Floor height (m)	Air-conditioned area (m^2)	Window area (m^2)	Window-wall ratio
Office	3.2	11200	2570	0.36
Shopping mall		4800	630	0.49

Total		16000	3200	0.38

Table 4 Detailed data of building envelope

A. External wall for 1st floor to 15th floor

material	Thickness(m)	Conductivity(W/mK)	Density(kg/m^3)	Specific heat(J/kgK)
White mosaic tile	0.005	1.5	2500	840
Cement render	0.01	0.72	1860	840
Concrete panel	0.1	2.16	2400	657
Gypsum plaster	0.01	0.51	1120	960

B. External wall for 15th floor to 27th floor

material	Thickness(m)	Conductivity(W/mK)	Density(kg/m^3)	Specific heat(J/kgK)
Black glass tile	0.008	1.05	2500	610
Mineral wool felt insulation	0.075	0.039	50	1470
Aerated insulation	0.05	0.024	1.3	1004
Pressed steel panel	0.002	45	7800	480

C. Roof

material	Thickness(m)	Conductivity(W/mK)	Density(kg/m^3)	Specific heat(J/kgK)
Concrete tiles	0.025	1.1	2100	657
Asphalt	0.02	1.2	2300	1700
Cement screed	0.05	0.72	1860	840
Expanded polystyrene	0.05	0.035	23	1470
Concrete	0.15	2.16	2400	657
Gypsum plaster	0.01	0.51	1120	960

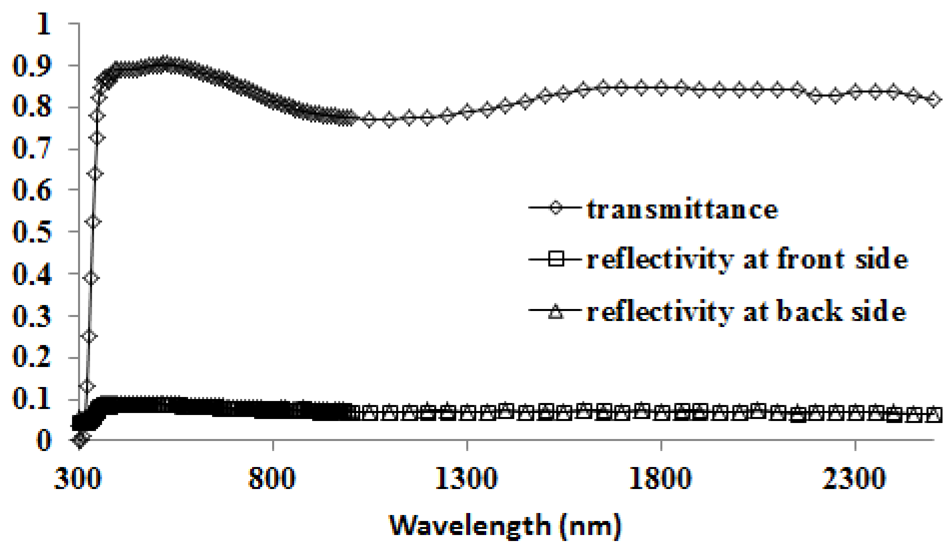
D. Glazing property

Properties	data
Solar transmittance at normal incidence	0.834
Front side solar reflectance at normal incidence	0.075
Back side solar reflectance at normal incidence	0.075
Visible transmittance at normal incidence	0.899
Front side visible reflectance at normal incidence	0.083
Back side visible reflectance at normal incidence	0.083
Infrared transmittance at normal incidence	0
Front side infrared reflectance at normal incidence	0.84
Back side infrared reflectance at normal incidence	0.84

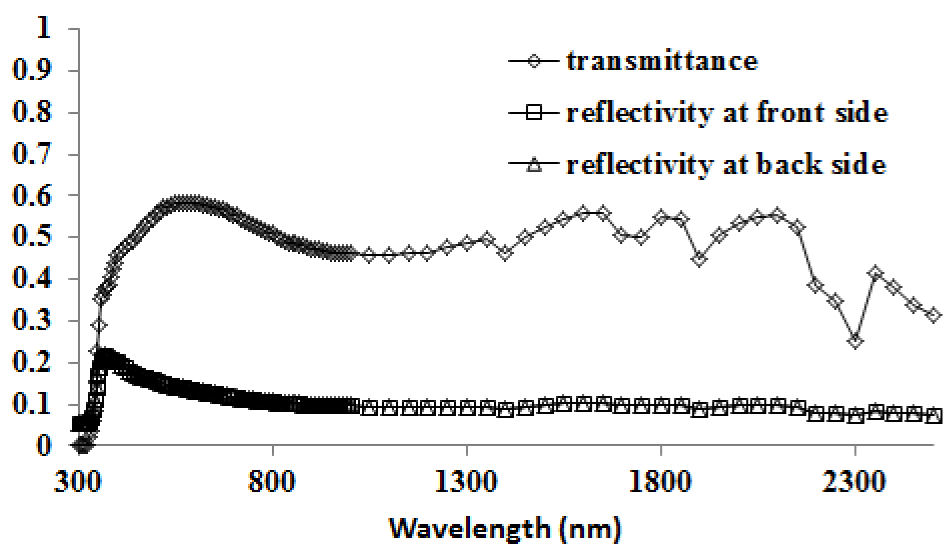
Results and discussions

1. Test result of the silica aerogel window sample

For the optical feature test, three parameters should be measured, respectively transmittance, front side reflectivity and back side reflectivity. A UV-visible infrared spectrophotometer is applied to test the window sample's optical features within the wavelength range of 300 to 2500 nm. The test is conducted in accordance with ISO 9050: 2003 "Glass in building – Determination of light transmittance, solar direct transmittance, total solar energy transmittance, ultraviolet transmittance and related glazing factors". A reference window sample was also prepared in order to give an intuitive impression of the silica aerogel filling's impact on the window sample's performance. The reference window sample was identical to the silica aerogel window sample except there was no silica aerogel filling in between the two single glass layers. Figure 6 presents the optical features of these two samples.



A. Reference window sample



B. Silica aerogel window sample

Figure 6 Optical features test result

Obviously, the application of silica aerogel filling largely reduces the transmittance along the light wavelength. Before the filling of silica aerogel, the transmittance of the window sample is around 0.8, while the utilization of silica aerogel reduces the transmittance to around 0.45. The reflectivity also rises slightly.

For the measurement of thermal conductivity, a plane-conductivity meter was applied. The test was conducted with accordance to GB/T10294-2008: “Thermal insulation - Determination of steady-state thermal resistance and related properties - Guarded hot plate apparatus”. The thermal conductivity of the silica aerogel window sample was measured to be around 0.13W/mK, the U factor of the silica aerogel window sample can be calculated to be around 2.8 W/m2K. While the thermal conductivity of the reference window sample was measured to be about 0.15W/mK, and the U factor of the silica aerogel window sample can be calculated to be around 3.2 W/m2K. After obtaining the thermal and optical parameters of the silica aerogel window sample, a further simulating investigation is possible.

2. Annual energy performance simulation

Figure 7 present the simulation result of the annual space cooling load within the model building, In Base Case, the glazing utilized on building envelope was the glazing listed in Table 2. In Aerogel Case, the glazing on building envelope was silica aerogel glazing system.

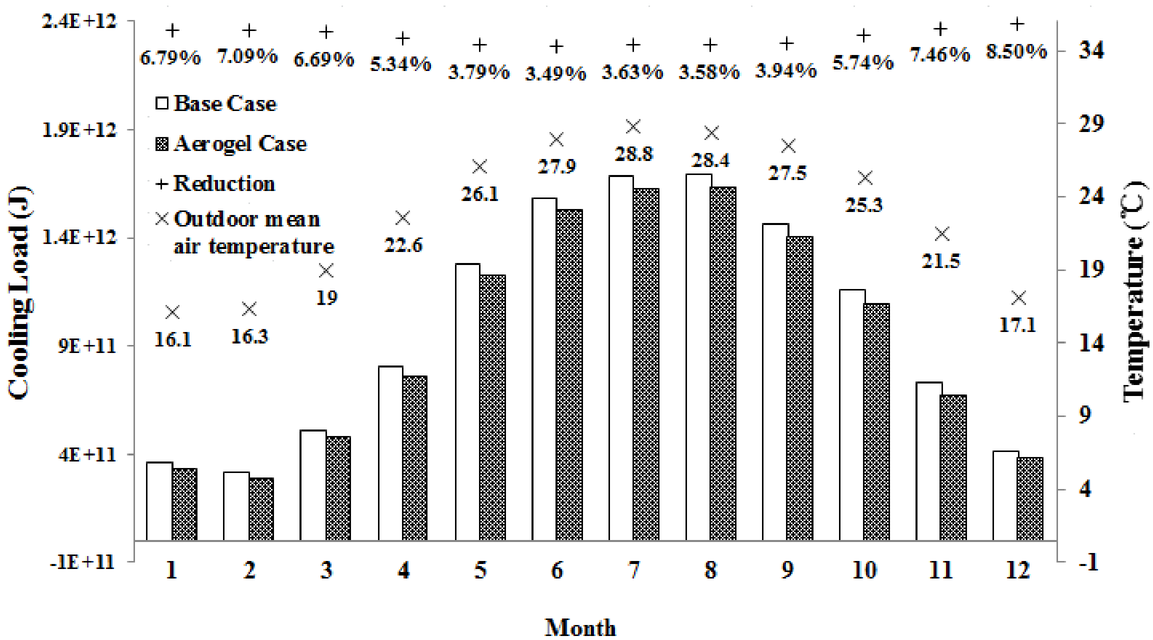
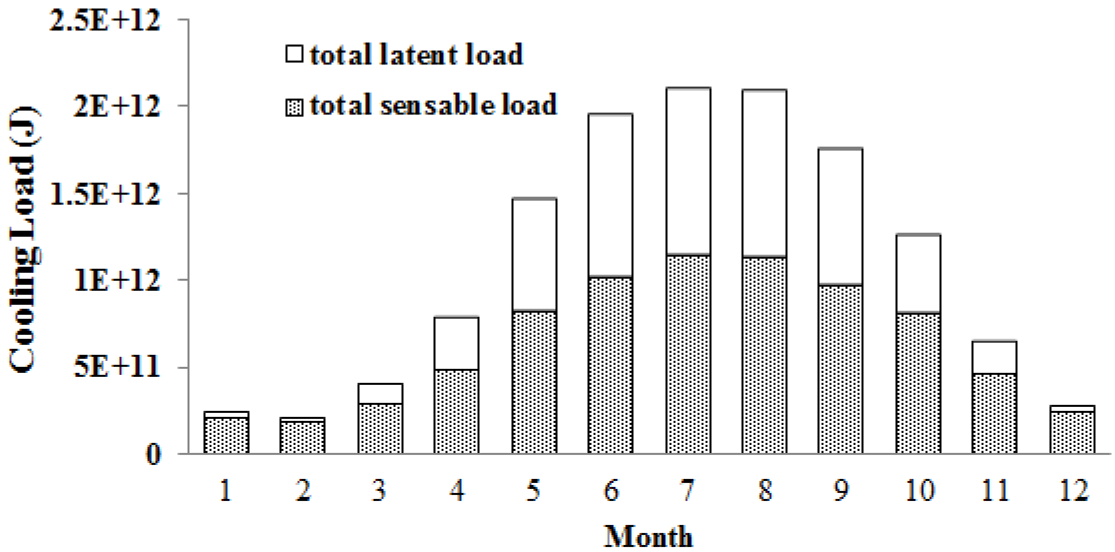


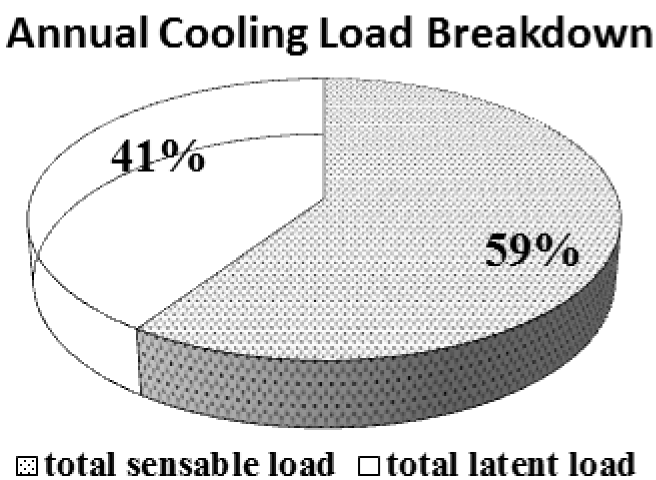
Figure 7 Thermal performance of silica aerogel window system

After utilization of silica aerogel window, the cooling load is reduced. In the hottest months, the cooling load can be cut by 3.5% ~ 4%. From November to March, the cooling load reduction can be around 7%. However it should be noted that during this period, not all the space cooling load would be handled by air-conditioning system, introducing in larger amount of fresh air would help to reduce the air-conditioning system energy consumption. According to this consideration, in Figure 7 only data during cooling season can serve as a reference. So the effective reduction of silica aerogel window should be the reduction during April to October, which is the typical cooling season in Hong Kong. From Figure 7, during the cooling season, the Base Case cooling load is around 9.67×10^{12} J, while the Aerogel Case cooling load is around 9.28×10^{12} J. A reduction of around 4×10^{11} J is expected, which is about 4% of the total air-conditioning system load. The model building had a total air-conditioned area of 16000 m^2, and a total window area of 3200 m^2. The annual reduction can also be expressed as 2.5×10^7 J/m^2 air-conditioned area, or 1.25×10^8 J/m^2 window area.

It seems that the reduction part only takes a small proportion in the building's total cooling load. A detailed breakdown analysis of the building's cooling load is presented as follow. Hong Kong is located within a humid subtropical climate zone, which result in a considerable proportion of latent load within the total cooling load. Figure 8 gives the percentage of latent load within the total annual cooling load.



A. The proportion of latent load in a monthly basis

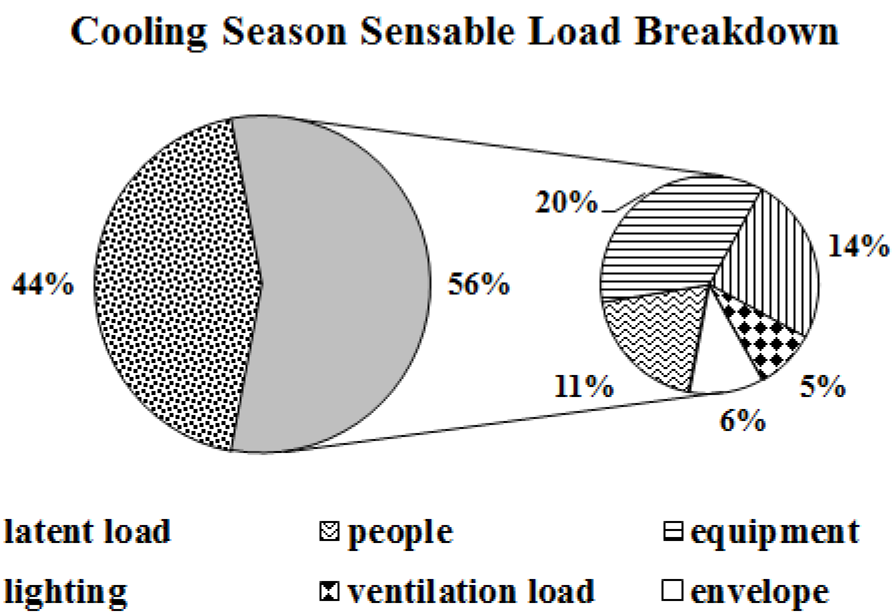


B. The proportion of latent load annually

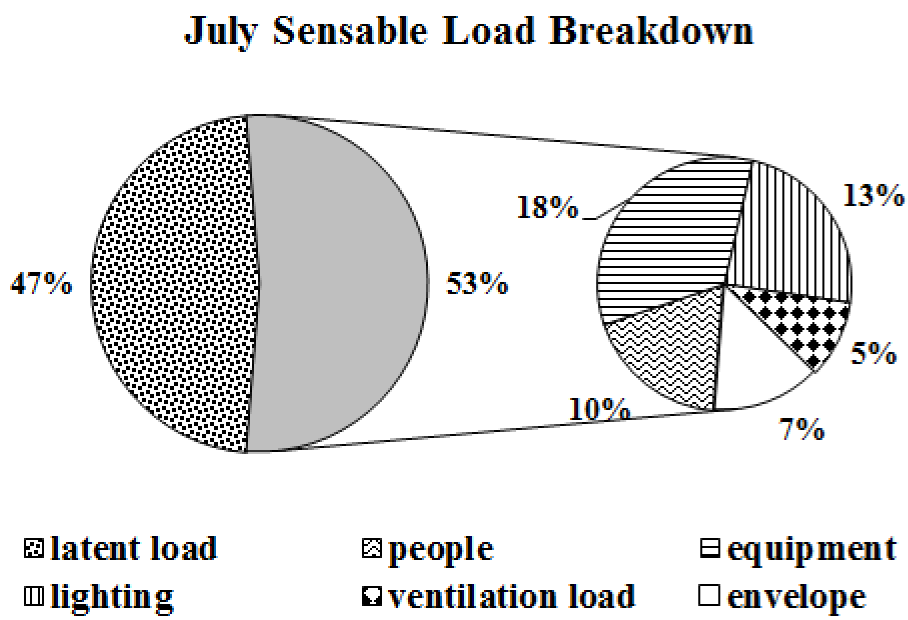
Figure 8 Proportion of latent load within the total cooling load in Hong Kong

From Figure 8 it is clear that the sensible load only less than 60% of the total cooling load in Hong Kong, which means considering sensible part only, the application of silica aerogel window can achieve a reduction of 6% ~ 7%. It is also clear that from November to March the latent load is relatively small, which confirms our previous statement that fresh air can be introduced to handle the space cooling load in buildings.

A detailed sensible breakdown is presented in Figure 9. It is clear that cooling load caused by envelope heat gain does not account for a large part in the sensible cooling load. In cooling season, the cooling load caused by envelope heat gain takes 6% of the building's total cooling load. In July which is the hottest month in summer, the cooling load caused by envelope heat gain is 7% of the total cooling load. This fact indicates that, application of silica aerogel window can reduce almost 60% ~ 70% of the cooling load caused by envelope heat gain. From the envelope design point of view, the effect cannot be ignored.



A. Cooling season breakdown



B. July breakdown

Figure 9 Breakdown of sensible load

A simulation of one common shading-type low-e glazing was also conducted. Table 5 listed the optical features of the selected low-e glazing. The annual cooling load of low-e glazing case was compared with that of silica aerogel glazing case, so as to give a direct image of the silica aerogel glazing's thermal performance. The simulation result for the low-e glazing is shown in Figure 10. In cooling season, the cooling load in Low-e Case is around 9.31×10^{12} J, which is 3.7% lower than that in Base Case. The thermal performance of silica aerogel glazing is slightly better than the selected low-e glazing, which can serve as a reference for glazing selection during building envelope design.

Table 5 Optical features of the low-e glazing

Properties	data
Solar transmittance at normal incidence	0.598
Front side solar reflectance at normal incidence	0.074
Back side solar reflectance at normal incidence	0.109
Visible transmittance at normal incidence	0.805
Front side visible reflectance at normal incidence	0.087
Back side visible reflectance at normal incidence	0.096
Infrared transmittance at normal incidence	0
Front side infrared reflectance at normal incidence	0.84
Back side infrared reflectance at normal incidence	0.204

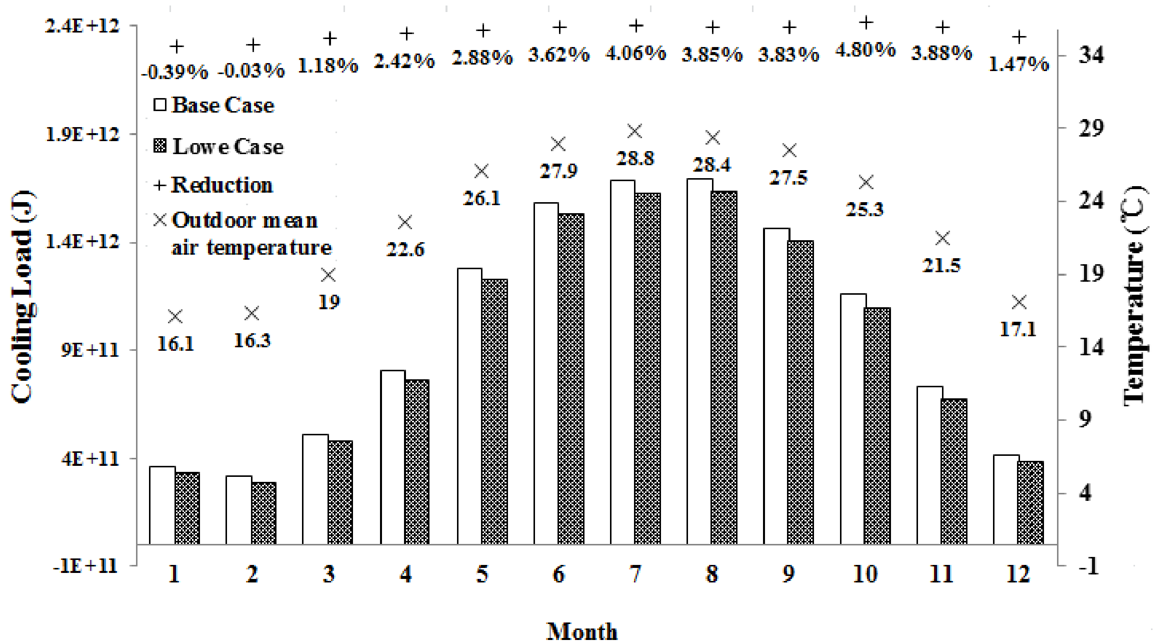
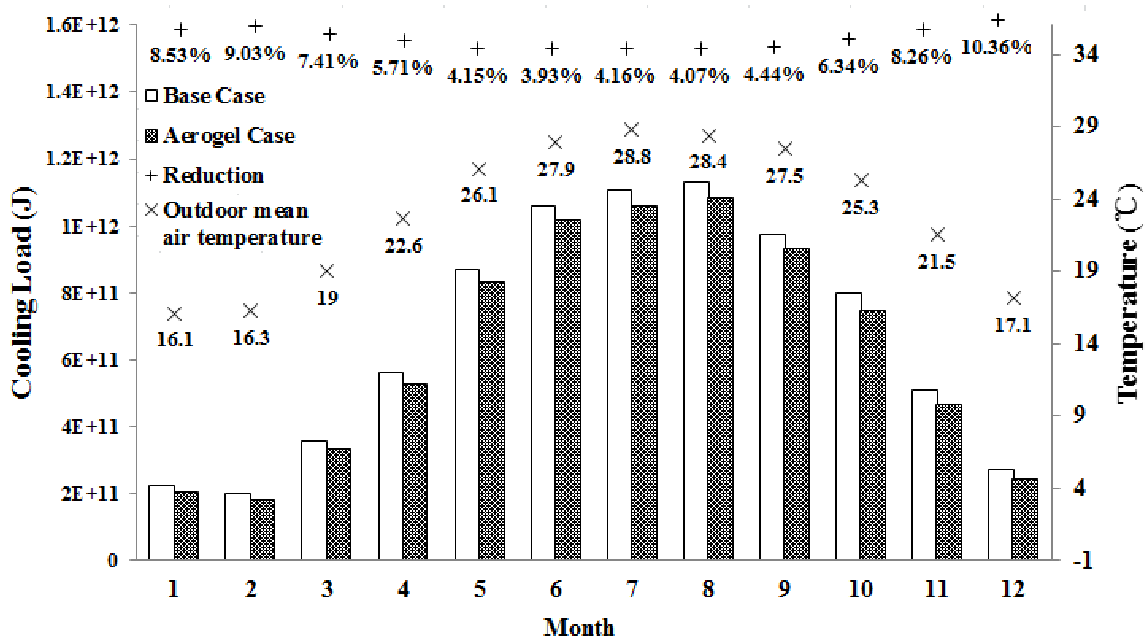
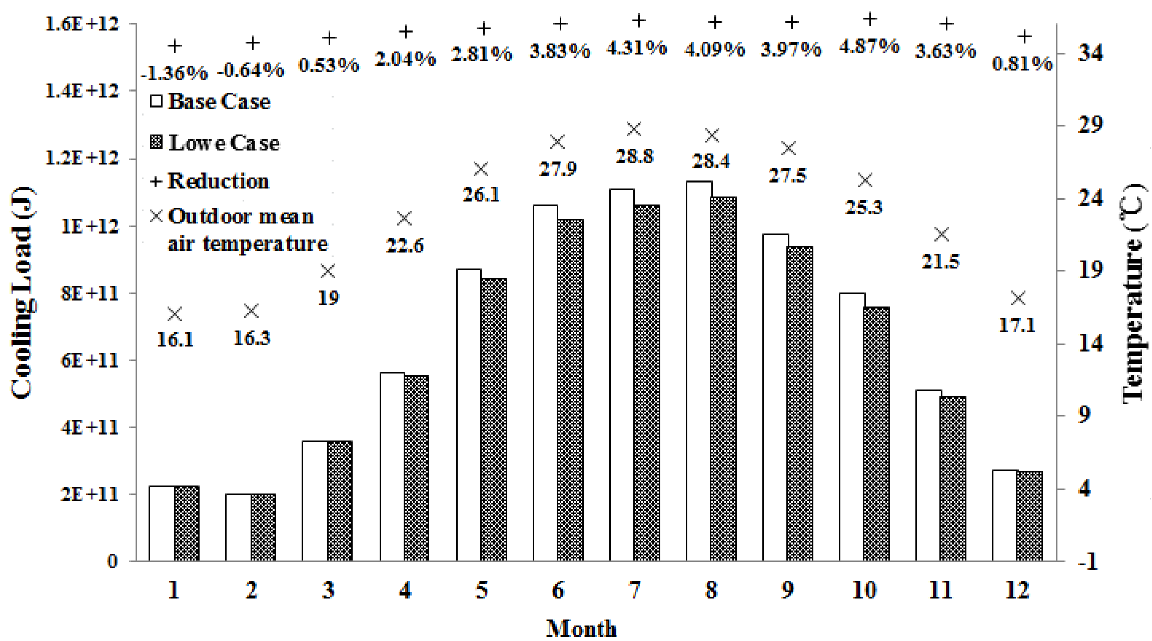


Figure 10 Thermal performance low-e glazing

Comparing Figure 7 with Figure 10, it can be observed that during June to September, the performance of low-e glazing is a bit better, while in April, May and October, the performance of silica-aerogel glazing surpasses. It should be noticed that the model building is consisted of two parts: the office part and the shopping mall part. Figure 10 and Figure 11 separate the cooling load from office and shopping mall apart to see the impact of building type on the performance of different glazing materials.

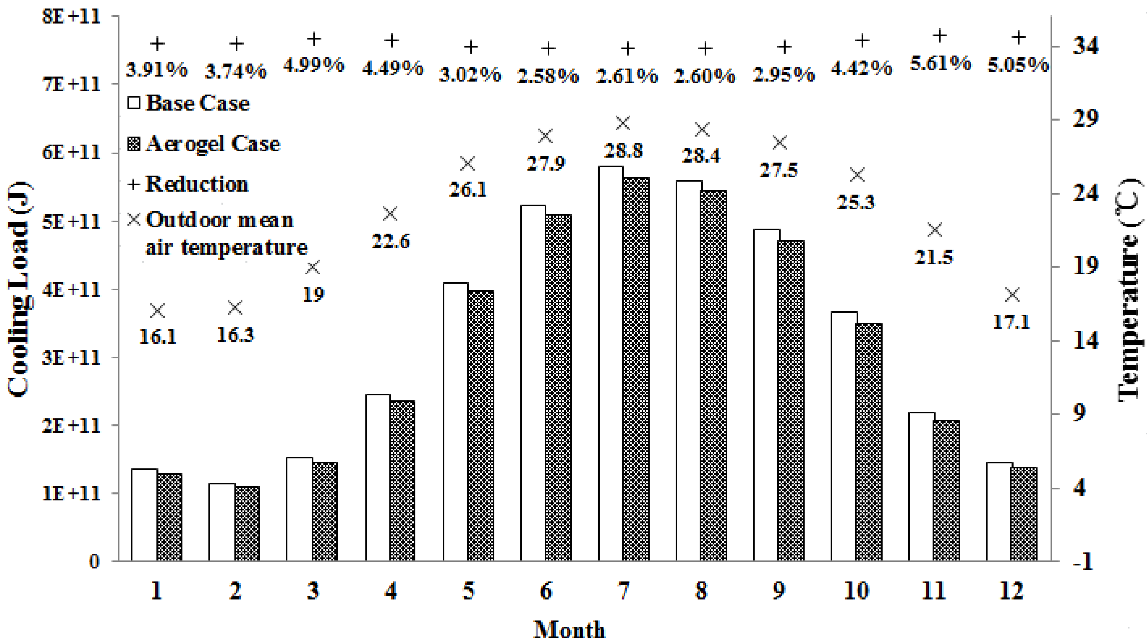


A. Silica aerogel glazing

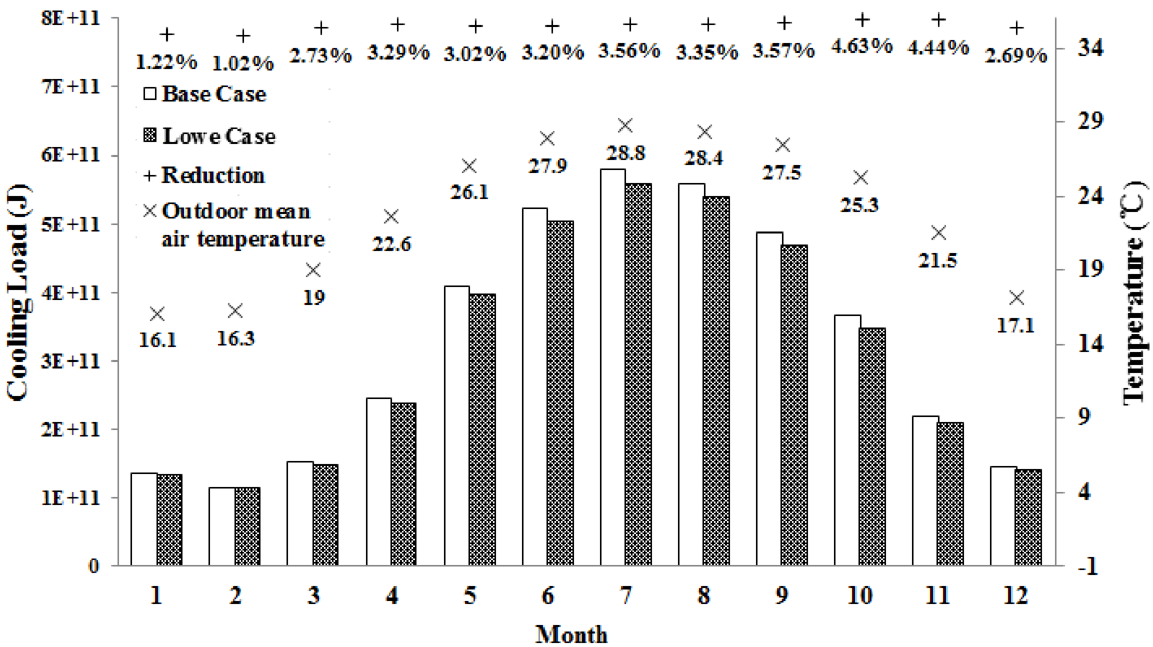


B. Low-e glazing

Figure 11 Performance of different glazing materials in office floors



A. Silica aerogel glazing

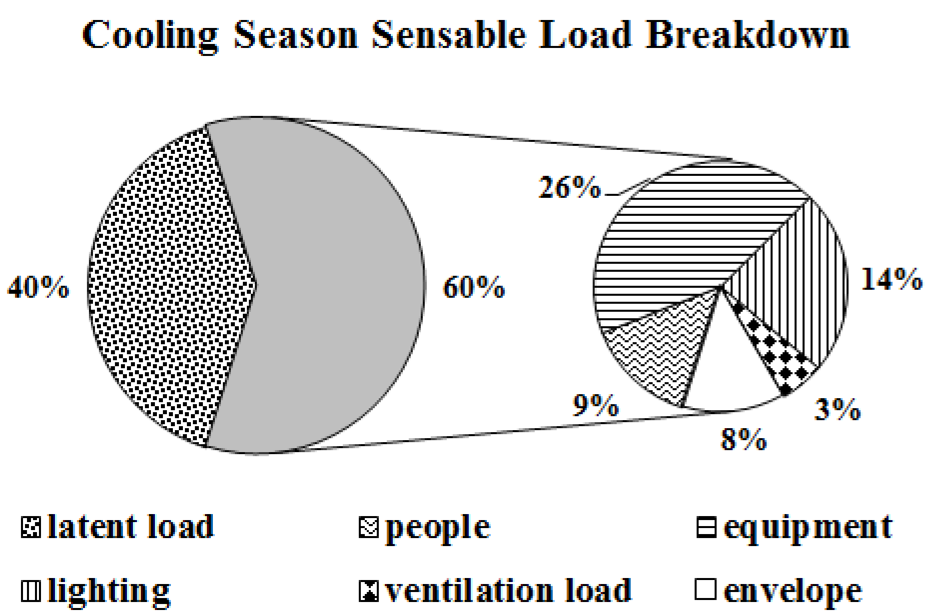


B. Low-e glazing

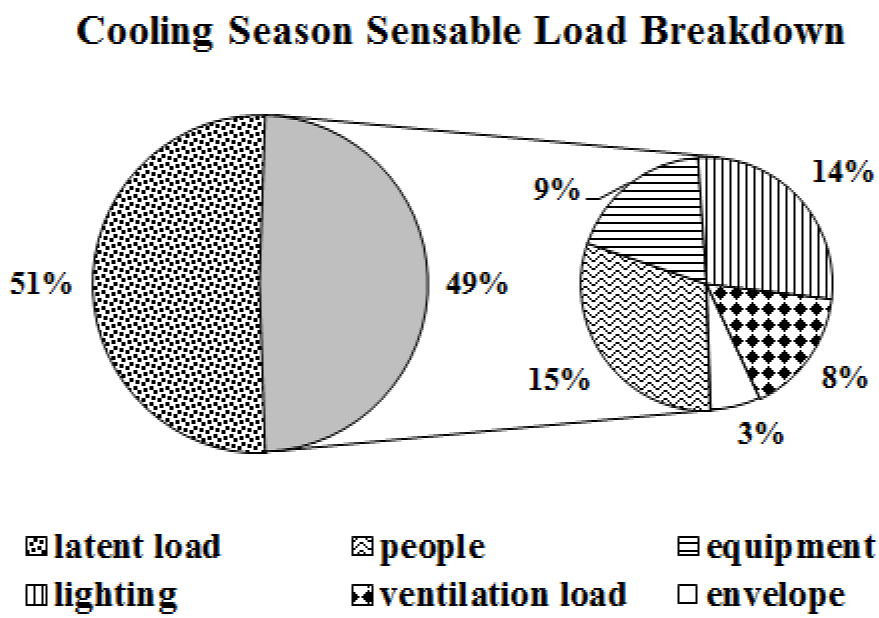
Figure 12 Performance of different glazing materials in shopping mall floors

From Figure 11 and Figure 12, obviously in office section, the performance of silica aerogel glazing is better than that of low-e glazing in most time of the cooling season, while in shopping mall section, the low-e glazing is a better choice. The reason may lie in the proportion of internal heat source take in the total cooling load. Figure 13 gives the breakdown of sensible load in office and shopping mall sections during cooling season separately. The cooling load caused by building envelope heat gain takes about 8% in office region. While in shopping mall region, the value is only 3%.

The low-e glazing selected in the study is a shading-type low-e glazing. The low-e coating is located in the inner surface of the outer glazing layer. This structure prevents the absorbed heat from radiating to the interior space. With the same reason, less heat radiated by the interior heat source can be projected back into the indoor space. It can be concluded that the energy performance of silica aerogel glazing is affected by the composition of the building's cooling load structure. The smaller the interior heat gain's proportion takes in the total cooling load, the better the silica aerogel glazing performs.



A. Office floors



B. Shopping mall floors

Figure 13 Detailed cooling load breakdown in different building floors

Conclusion and Future work

A silica aerogel window sample was first manufactured. The thermal and optical features were tested. An EnergyPlus based simulation was then conducted to test the annual energy performance of the proposed glazing system in the cooling-dominant Hong Kong climate. A comparison is made between the proposed glazing system and a common shading-type low-e glazing is also adopted.

The main thermal and optical features of our silica aerogel window sample are first measured. The transmittance of window sample showed a significant decrease when compared with the reference sample. The transmittance dropped from around 0.8 to around 0.45 within the spectrum. The reflectivity also rose slightly. The thermal conductivity is reduced from0.15W/mK to 0.13W/mK.

In the simulation study, a commercial building was constructed strictly based on the Hong Kong government's design guideline. An annual cooling load reduction of 1.25×10^8 J/m^2 window area was achieved, which is 2.5×10^7 J/m^2 air-conditioned area. The reduction took over 60% of the envelope-caused cooling load, and about 4% of the building total air-conditioning system load. It is also discovered that the energy performance of silica aerogel glazing is affected by the composition of the building's cooling load structure. The smaller the interior heat gain's proportion takes in the total cooling load, the better the silica aerogel glazing performs.

The work present in the paper is the first attempt of applying silica aerogel glazing in cooling-dominant climates. There exist several limits.

- Since there is no mature commercial production line in low latitude area, the silica aerogel window sample is produced by hand. The construction and packaging was way too rough. There exist conspicuous seams on the aluminum frame. The aluminum bracket also gets out into the glazing area in some places. All this factors may affect the thermal and optical performance of the window sample.
- The sealing method may not be the best choice.
- The filling of silica aerogel grain was also not perfect. Ideally, the aerogel grains should be contacted closely enough that no movement exist. At the same time the aerogel grains cannot be destroyed due to pressure. In our window sample, there is a possibility of crack forming after shaking hardly.
- It is not possible to conduct an accurate life cycle analysis or carbon/primary energy payback period analysis.
- The simulation study only considered the impact of proposed glazing system's application on air-conditioning system cooling load. The diffusing translucent feature of the silica aerogel window system may improve the indoor thermal comfort and reduce the possibility of glare, which are also important issues in glazing material's performance.

In our future work, more simulation work will be conducted to analysis the thermal and visual performance of the silica aerogel glazing. In the thermal simulation study, the operative temperature and occupant's PMV level will be investigated to evaluate the influence of silica aerogel window on indoor environment. In the visual simulation, the effect of silica aerogel window on glare prevention will be tested. The cooperation of conventional clear glazing and silica aerogel glazing will also be considered to achieve a balance between external view and glare elimination. A series of experimental studies will also take places. The actual performance of the proposed glazing system will be tested qualitatively and quantitatively. Factors such as weather condition and material thermal inertia will be studied.

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Reference

[1] Yu Huang, Jian-lei Niu, Tse-ming Chung, Study on performance of energy-efficient retrofitting measures on commercial building external walls in cooling-dominant cities, Applied Energy, 103(2013) 97-108.

[2] Orhan Aydin, Determination of optimum air-layer thickness in double-pane windows, Energy and Buildings, 32 (2000) 303-308.

[3] Andrea Gasparella, Pernigotto Giovanni, Francesca Cappelletti, Piercarlo Romagnoni, Paolo Baggio, Analysis and modeling of window and glazing systems energy performance for a well-insulated residential building, Energy and Buildings, 43(2011) 1030-1037.

[4] J. J. Finley, Heat treatment and bending of Low-E glass. Thin Solid Films, 351(1999) 264-273.

[5] S. S. Kistler, Coherent expanded aerogels and jellies, Nature, 127(1931) 741-741.

[6] Ruben Baetens, Bjørn Petter Jelle, Arild Gustavsen, Aerogel insulation for building applications: A state-of-the-art review, Energy and Buildings, 43(2011) 761-769.

[7] Erdem Cuce, PinarMertCuce,ChristopherJ.Wood,SaffaB.Riffat, Toward aerogel based thermal superinsulation in buildings: A comprehensive review, Renewable and Sustainable Energy Reviews, 34(2014) 273-299.

[8] Jun-Jie Zhao, Yuan-Yuan Duan, Xiao-Dong Wang, Bu-Xuan Wang, Radiative properties and heat transfer Characteristics of fiber-loaded silica aerogel composites for thermal insulation, International Journal of Heat and Mass Transfer, 55(2012) 5196-5204.

[9] Tao Xie, Ya-Ling He, Zi-Jun Hu, Theoretical study on thermal conductivities of silica aerogel composite insulating material, International Journal of Heat and Mass Transfer, 58(2013) 540-552.

[10] Tao Xie, Ya-Ling He, Zi-Xiang Tong, Wei-Xu Yan, Xiang-Qian Xie, Transient heat transfer characteristic of silica aerogel insulating material considering its endothermic reaction, International Journal of Heat and Mass Transfer, 68(2014) 633-640.

[11] Hai-Tong Yu, Dong Liu, Yuan-Yuan Duan, Xiao-Dong Wang, Theoretical model of radiative transfer in opacified aerogel based realistic microstructures, International Journal of Heat and Mass Transfer, 70(2014) 478-485.

[12] Gaosheng Wei, Yusong Liu, Xinxin Zhang, Fan Yu, Xiaoze Du, Thermal conductivities study on silica aerogel and its composite insulation materials, International Journal of Heat and Mass Transfer, 54(2011) 2355-2366.

[13] Gaosheng Wei, Yusong Liu, Xinxin Zhang, Xiaoze Du, Radiative heat transfer study on silica aerogel and its composite insulation materials, Journal of Non-Crystalline Solids, 362(2013) 231-236.

[14] C. Bi, G. H. Tang, Z. J. Hu, Heat conduction modeling in 3-D ordered structures for prediction of aerogel thermal conductivity. International Journal of Heat and Mass Transfer 73(2014) 103-109.

[15] Th. Stahl, S. Brunner, M. Zimmermann, K. Ghazi Wakili, Thermo-hygric properties of a newly developed aerogel based insulation rendering for both exterior and interior applications, Energy and Buildings, 44(2012) 114-117.

[16] Bo Yuan, Shuqiang Ding, Dongdong Wang, Gang Wang, Hongxia Li, Heat insulation properties of silica aerogel/glass fiber composites fabricated by press forming, Materials Letters, 75(2012) 204-206.

[17] Mark Dowson, Ian Pegg, David Harrison, Zahir Dehouche, Predicted and in situ performance of a solar air collector incorporating a translucent granular aerogel cover, Energy and buildings 49(2012) 173-187.

[18] K. Chen, A. Neugebauer, T. Goutierre, A. Tang, L. Glicksman, L. J. Gibson, Mechanical and thermal performance of aerogel-filled sandwich panels for building insulation, Energy and buildings, 76(2014) 336-346.

[19] Erdem Cuce, Pinar Mert Cuce, Christopher J. Wood, Saffa B. Riffat, Optimizing insulation thickness and analyzing environmental impacts of aerogel based thermal superinsulation in buildings, Energy and Buildings, 77(2014) 28-39.

[20] R. Caps, J. Fricke, Infrared radiative heat transfer in highly transparent silica aerogel, Solar Energy, 36(1986) 361-364.

[21] J. Fricke, R. Caps, D. Buttner, U. Heinemann, E. Hummer, Silica aerogel – a light-transmitting thermal superinsulator, Journal of Non-Crystalline Solids, 96(1987) 1167-1174.

[22] W. J. Platzer, M. Bergkvist, Bulk and surface light scattering from transparent silica aerogel, Solar Energy Materials and Solar Cells, 31(1993) 243-251.

[23] K. Duer, S. Svendsen, Monolithic silica aerogel in superinsulating glazings, Solar Energy, 1998(63) 259-267.

[24] K. I. Jensen, J. M. Schultz, F. H. Kristiansen, Development of windows based on highly insulating aerogel glazing, Journal of Non-Crystalline Solids, 350(2004) 351-357.

[25] J. M. Schultz, K. I. Jensen, F. H. Kristiansen, Super insulating aerogel glazing, Solar Energy Materials and Solar Cells, 89(2005) 275-285,

[26] J. M. Schultz, K. I. Jensen, Evacuated aerogel glazings, Vacuum, 82(2008) 723-729.

[27] M. Reim, A. Beck, W. Korner, R. Petrickvic, M. Glora, M. Weth, T. Schliermann, J. Fricke, CH. Schmidt, F. J. Potter, Highly insulating aerogel glazing for solar energy usage, Solar Energy, 72(2002), 21-29.

[28] M. Reim, W. Korner, J. Manara, S. Korder, M. Arduini-Schuster, H. P. Ebert, J. Fricke, Silica aerogel granulate material for thermal insulation and daylighting, Solar Energy 79(2005) 131-139.

[29] C. Buratti, E. Moretti, Experimental performance evaluation of aerogel glazing systems, Applied Energy, 97(2012) 430-437.

[30] C. Buratti, E. Moretti, Glazing systems with silica aerogel for energy savings in buildings, Applied Energy, 98(2012) 396-403.

[31] Y.P. Zhou, J.Y. Wu, R.Z. Wang, S. Shiochi, Y.M. Li, Simulation and experimental validation of the variable-refrigerant-volume (VRV) air-conditioning system in EnergyPlus, Energy and Buildings. 40(2008) 1041-1047.

[32] Paulo Cesar Tabares-Velasco, Craig Christensen, Marcus Bianchi, Verification and validation of EnergyPlus phase change material model for opaque wall assemblies, Building and Environment. 54(2012) 186–196.

[33] Robert H Henninger, Michael J Witte, Drury B Crawley, Analytical and comparative testing of EnergyPlus using IEA HVAC BESTEST E100-E200 test suite, Energy and Buildings. 36(2004) 855-863.

[34] Hong Kong Government, Code of practice for overall thermal transfer value in buildings, 1995.

[35] Hong Kong Government, Building Energy Code, 2007.