https://doi.org/10.1016/j.conbuildmat.2015.06.053.

Energy and visual performance of the silica aerogel glazing system in commercial buildings of Hong Kong

Yu Huang[a], Jian-lei Niu[a,1]

[a] Department of Building Service Engineering, Faculty of Construction and Environment, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong SAR, China

Abstract: Indoor environment quality (IEQ) is a comprehensive index to assess the performance of a building. To achieve a high IEQ while still retaining low energy consumption level is an exciting challenge for designers and owners of buildings. In this paper, a silica-aerogel filled super-insulating glazing system was considered under sub-tropical climate condition. Its performance in the IEQ control was studied by simulation. A commercial building model in Hong Kong was constructed for case study. In the thermal comfort study, a commonly used shading type low-e glazing was also simulated as a reference. Three different control strategies, namely space temperature control, operative temperature control and PMV control were applied to discuss the performance of the glazing systems. In the visual comfort study, two different glazing arrangements, namely replacing the conventional single clear glazing by the proposed silica aerogel glazing and a combination of the single clear glazing and the silica aerogel glazing were considered. The result indicated that from the aspect of thermal comfort, the performance of silica aerogel glazing was significantly better than that of the single clear glazing. Compared to the single clear glazing, the silica aerogel glazing could retain a higher indoor thermal comfort level while the energy consumption of HVAC system was down by at least 4%. The performance of the silica aerogel glazing was almost equal to that of the selected low-e glazing. As the thermal comfort requirement got stricter, the performance of the silica aerogel glazing became better. From the visual comfort point of view, the glare effect and near-window bright zone could be reduced significantly while indoor illumination level still met the requirement.

Keywords: silica aerogel glazing system, thermal comfort, visual comfort, energy consumption, indoor environment quality

[1]Corresponding author. Tel: +852 2766 7781; Fax: +852 2765 7198;

E-mail addresses: 10900570r@polyu.edu.hk (Yu Huang), bejlniu@polyu.edu.hk (Jian-lei Niu)

1. Introduction

Indoor environment quality (IEQ) is a newly developed index to describe the condition inside a building related to the occupant's health and wellbeing. A comfortable indoor environment includes many aspects, such as thermal comfort, visual comfort, acoustic comfort and indoor air quality, etc. All these aspects interact with each other and may have consequences on the overall indoor comfort and building energy consumption. IEQ has been adopted in several building grading systems [1-3].

Maintaining satisfactory comfort indoor conditions for the occupant is one of the primary concerns in many air-conditioned commercial buildings. However, in many cases the maintaining of satisfactory IEQ has a conflict effect toward the energy conservation principle. Providing and maintaining acceptable comfort level whilst keeping energy costs and carbon emissions low is an exercise that requires designers, owners and users of buildings to work together, trying to make the right balance between energy saving imperatives and providing comfort.

To achieve a balance between IEQ and low energy consumption requires a good structure design, high performance equipment and advanced building materials. There had been large amount of literatures on improving indoor environment quality by good building design and appropriate air-conditioning systems. With respect to the building materials, relating studies were limited. In fact, building material, especially window material plays an important role in the control of indoor environment quality. The size, thermal properties as well as optical parameters of window element would affect the amount of unwanted solar radiation as well as the uncomfortable glare, so as to affect the thermal comfort and the visual comfort status.

In this paper, a silica aerogel glazing system was proposed and stimulatingly studied. The glazing system was a sandwich-type window with two layers of single clear glass at both sides and the aerogel product filled in between. The performance of the proposed glazing system in the IEQ control was analyzed from the aspects of thermal comfort and visual comfort. A typical commercial building model in Hong Kong (which is a typical cooling-dominant subtropical city) was constructed as a case study. Two famous simulation tools were involved in the analysis of the proposed glazing system. EnergyPlus was applied to test the performance of the proposed glazing system on the indoor thermal comfort. Radiance was applied to test the performance of the proposed glazing system on the visual environment. It is expected that the result could serve as a reference for glazing material selection during building design process.

2. Literature review

2.1. Study of glazing's impact on IEQ in buildings

As mentioned above, improving indoor environment quality by good building design and air-conditioning system attracted the major attention of the professionals. There were many studies discussing these topics. However, less attention was paid to the impact of building materials, especially the glazing on the IEQ of buildings. The number of relating literatures was quite limited.

Not until early last decade, researchers started to pay attention to the glazing area of building envelope, trying to determine the impact of glazing on the thermal comfort and visual comfort inside the building.

2.1.1. Study on thermal comfort performance of glazing

In the year 2002, Kim et al. started to notice the impact of façade glazing on occupant's thermal and visual comfort. They conducted a survey and a synchronous measurement in an office building which received many prizes for its architectural design. A systematic simulation is also involved. From the result they discovered that at least in the year 2002, the architects designed glazing area in their buildings according to aesthetics without paying any attention to occupant's comfort and energy consumption. They claimed that the large area of single glazing applied in the building caused a high air-conditioning energy consumption and extensive complain of thermal and visual un-comfort. They suggested that double-skin façade and necessary shade be applied so that the comfort and energy performance of building façade could be improved [4]. Later, Menzies and Wherrett did a survey study on the impact of window glazing on energy performance and occupant thermal comfort. They reached the conclusion that during the year 2004, architects started to consider occupant thermal comfort as a design issue. However, they still did not pay much attention on the energy consumption [5]. Roche and Milne developed an intelligent ventilation system which was supposed to be considering both energy consumption and occupant thermal comfort. They included the impact of window size on the performance of their proposed ventilation system and claimed that with a smaller window size, their ventilation system would work better [6]. Chaiyapinunt et al. tried to give a rating for different window applications in Bangkok mathematically. During their rating analysis they considered heat transmission and thermal comfort simultaneously. Instead of using existing simulation tools, they developed their own calculation model to get the heat transfer result. In order to ensure the accuracy, they also applied experiment data to validate the model. According to the result, they claimed that the energy and comfort performance of glazing material depend totally on their spectral properties, thus selection of glazing material should take heat transmission, thermal comfort, light transmission and appearance into consideration [7]. Stegou-Sagia et al. also made a simulation study on the impact of double-layer glazing on thermal comfort and energy consumption [8]. Singh et al. conducted a simulation study on 15 different types of glazing system, trying to test their impacts on human thermal comfort under Indian climates. They found obvious diversion among different glazing systems. The largest difference could be as high as 30%. They also discovered that in cold climate almost all glazing systems could not meet the comfort requirement due to the lack of protection [9]. Hwang and Shu implemented a simulation study to see the influence of different glazing types on the indoor thermal comfort level. During their study, they introduced in a new index named ENVLOAD, which mainly reflected the orientations and physical properties of glazing components to make their result applicable on different buildings. They claimed that different glazing types had a large affection on thermal comfort. They also made some discussion on the glazing performance under the PMV-based control strategy and discovered that with lower ENVLOAD value, the energy saving potential got larger [10]. Yao and Zhu conducted a simulation study on the comprehensive performance of thermotropic windows. They claimed that in west-facing rooms, application of thermotropic window could reduce 70% uncomfortable condition compared with conventional clear glazing. They also claimed that the energy consumption could be reduced by 19% with the application of thermotropic window [11]. Serra et al. conducted an experiment on the performance of a ventilated double-skin façade to see its energy efficiency and thermal comfort performance. They did a series of measurement considering different air flow rates, different shading devices as well as different glazing types under winter heating and summer cooling situation. They claimed that the comprehensive performance of the double-skin façade was largely improved with air ventilation in between. With the same experiment system, they also tested the performance of a glazing system with the adoption of phase change material and also found a considerable improvement in the overall performance [12, 13]. Tzempelikos et al. developed a thermal comfort model to describe the impact of glazing and shading properties on the occupant thermal comfort. A validation was also made between the thermal comfort model and measurement data. They claimed that their model could show in general terms that how thermal comfort in perimeter zones be affected by the building envelope [14]. Stavrakakis et al. made a CFD simulation to study the impact of window opening on the thermal comfort situation within a natural ventilation room [15]. Cappelletti et al. conducted a simulation study to see the energy performance of different glazing design under controlled thermal comfort condition. During the simulation they kept the thermal comfort index within a monitored room at a certain level, and recorded the energy consumption under different glazing components. They reached the best choice of glazing materials for three different cities: Rome, Milan and Paris. [16]

2.1.2. Study on visual comfort performance of glazing

While the windows server as the main device of daylighting, direct sunlight through the window openings can cause the glare problem and the excessive contrast between the zone close to the window and that in the opposite end of the room. The majority of existing literatures focused on the application of shading device and the interacting of different control strategies [17-20]. With respect to visual comfort performance of glazing, literatures were quite rare.

Lee and Tavil applied DOE-2 to simulate the electrochromic window to study the performance of the electrochromic window and overhang combination. Their result indicated that compared with the low-e glazing which is state-of-art at that moment, the electrochromic window with overhang could reduce the energy consumption by around 10% while no visual un-comfort occurred [21].

Ochoa and Capeluto developed a program named NewFacades, which was expected to be an advice tool during the early design stage of building envelope construction. By cooperation with other building simulation program such as EnergyPlus, the program would calculate the energy performance and visual comfort score of variable façade alternatives. The designer could make appropriate selection according to the result [22]. Ochoa et al. also proposed a procedure to evaluate the performance of window opening by minimize the energy consumption and avoiding the visual un-comfort. They then conducted a simulation work to study the effect of window size on the window performance using their procedure. They claimed that with their method an optimum result could be reached in most cases. They also claimed that windows without any protection could barely meet the acceptable criteria [23].

Cannavale et al. tested the visual comfort performance of smart photovoltachromic windows through an experiment. They claimed that compared to clear glazing, the application of photovoltachromic window could eliminate uncomfortable glare two times more effectively. The period that occupant felt visual comfortable also become 2.5 times longer compared with clear glazing case [24].

2.2. Study on silica aerogel glazing system

Silica aerogel is a porous material which was first created by Kistler in 1931 [25]. Silica 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.

Silica aerogel was first introduced in building construction as an insulating material applied for wall and roof surface. Many researchers reported their studies on the silica aerogel insulation application [26-30]. Not until the 1980s, some researchers had considered silica aerogel as a potential transparent insulation material which may be applied in super insulation windows. There have been about three other research teams conducting studies on silica aerogel glazing system. All of these teams are located in Europe.

Jensen et al. from Technical University of Denmark developed a monolithic silica aerogel transparent glazing and had their glazing sample tested. They claimed that their sample had a less than 0.7 W/m^2K heat-loss coefficient and a 76% solar transmittance in the center [31, 32]. Later, they conducted a 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 [33].

Reim et al. in Germany also developed their own silica aerogel glazing system. They claimed that their glazing sample could achieve a solar energy transmittance of 35% [34, 35].

Buratti and Moretti from University of Perugia also investigated the application of silica aerogel glazing. They prepared several sandwich-type aerogel glazing samples with different thicknesses and conducted a test on the thermal and acoustic performance [36, 37]. In their latest publication, they conducted an on-site measurement to assess the impact of silica aerogel glazing on building indoor environment quality from the aspects of lighting and acoustics [38].

3. Methodology

3.1. Preparation of silica aerogel glazing system

A silica aerogel window sample was constructed for the thermal and visual properties test. Once the properties of the silica aerogel window sample were obtained, further simulation study could be processed.

The window sample was a sandwich-type glazing system. The glazing layers on both sides were formed by 6mm thick single clear glass, while the silica aerogel powder was filled in between the two glass layers. The edge of the glazing system was sealed by aluminum bracket and pressed polystyrene. Figure 1 shows the sketch of the window sample. The silica aerogel material applied in the glazing system was supplied by the Cabot Corporation. Table 1 presents the silica aerogel product features.

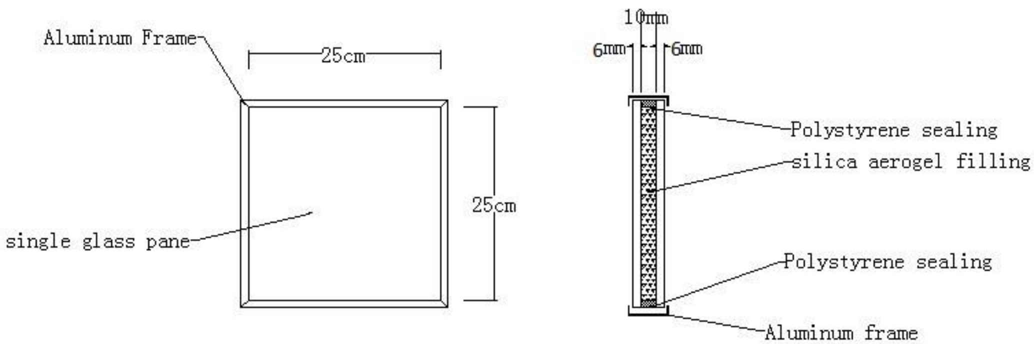


Figure 1 Diagrammatic sketch of the silica aerogel window sample

Table 1 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

The appearance of the packed window sample is displayed in Figure 2 below. A thermal feature test and an optical feature test were conducted right after the window sample was ready. In the thermal feature test, the conductivity was measured with a plane-conductivity meter. The thermal conductivity of the silica aerogel window sample was measured to be around 0.13W/m·K. The U value of the silica aerogel window sample was calculated to be around 2.8 W/m^{2}K. In the optical feature test, three major optical parameters, namely transmittance, front side reflectivity and back side reflectivity were measured. The optical measurement result was presented in Figure 3.

Figure 2 Appearance of the silica aerogel window sample

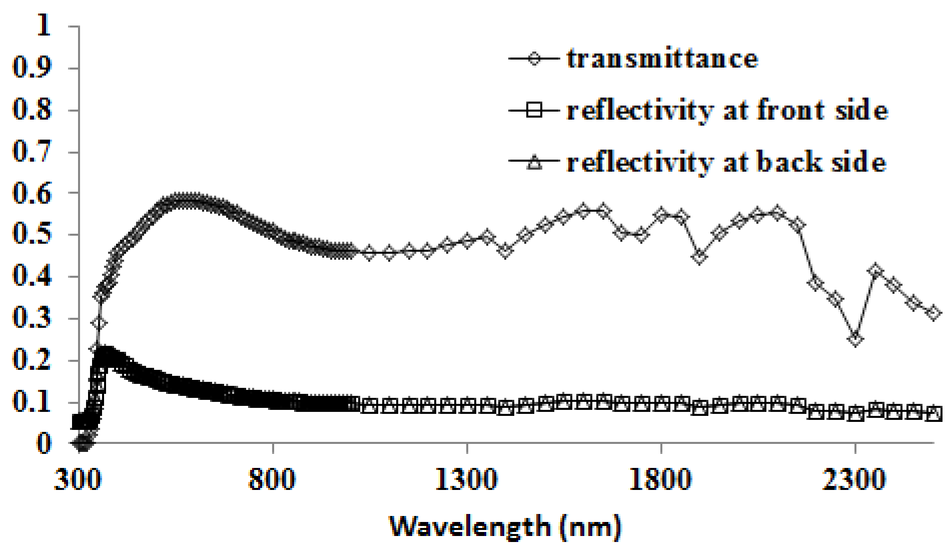


Figure 3 Optical features test result

3.2. Simulation set up

In this paper, two most important aspects of IEQ assessment, respectively thermal comfort and visual comfort were focused to assess the performance of silica aerogel window system. Two most popular simulation programs, namely EnergyPlus and Radiance were applied in the simulation study.

3.2.1. Thermal simulation set up

The thermal environment inside a typical commercial building in Hong Kong was selected for the case study. The simulation model of the commercial building was constructed strictly according to the reference building from the official guideline of Hong Kong Government [39]. It had one basement floor and 27 above ground floors. The first three floors were used as shopping mall. The 4th and 5th floors were car park. The rest floors were used as office. The office area and shopping mall area were air-conditioned. The densities and schedules of occupant, lighting, equipment as well as air-conditioning were defined strictly according to the design guideline of Hong Kong Government [40]. The appearance of the building model is presented in Figure 4. The arrow in the figure indicated the north direction. During the simulation, the simulation time step was 10 minutes. The detailed building envelope data is listed in Table 2.

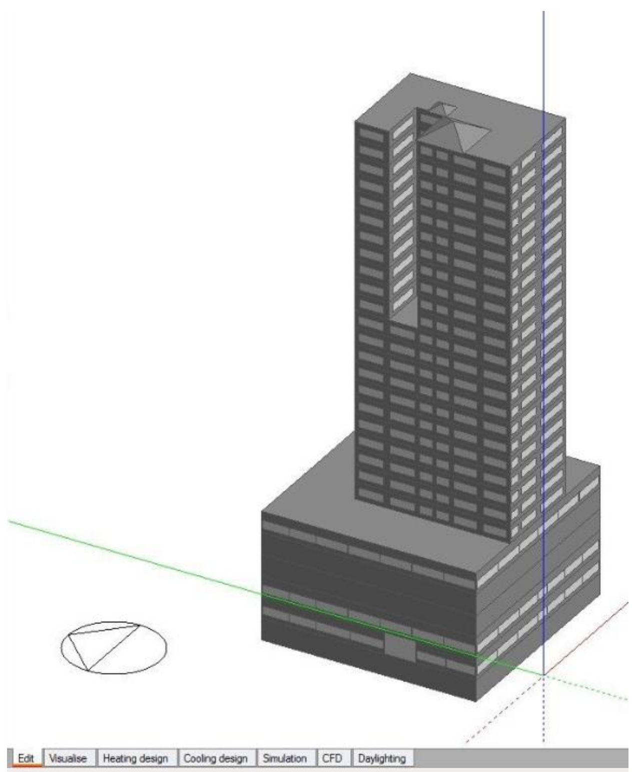


Figure 4 Outward appearance of the model building

Table 2 Detailed data of building envelope

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

material	Thickness(m)	Conductivity(W/m·K)	Density(kg/m^3)	Specific heat(J/kg·K)
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/m·K)	Density(kg/m^3)	Specific heat(J/kg·K)
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/m·K)	Density(kg/m^3)	Specific heat(J/kg·K)
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

During the study, a widely applied shading-type low-e glazing was also simulated, serving as a reference of difference between the proposed silica aerogel glazing system and state-of-art energy-efficient glazing product. The optical features of the selected low-e glazing are listed in Table 3.

Table 3 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

In order to make a more accurate discussion on the thermal comfort aspect, three different control strategies were applied in the simulation, namely space temperature control, space operative temperature control and PMV control.

3.2.2. Visual simulation set up

The visual simulation was based on the same model building. Typical separated rooms facing different orientations were referred so that the visual performance on different moments could be analyzed. The surface materials of the separated rooms were strictly defined according to the official guideline of Hong Kong Government [39]. Figure 5 presents the schematic of the visual simulation process.

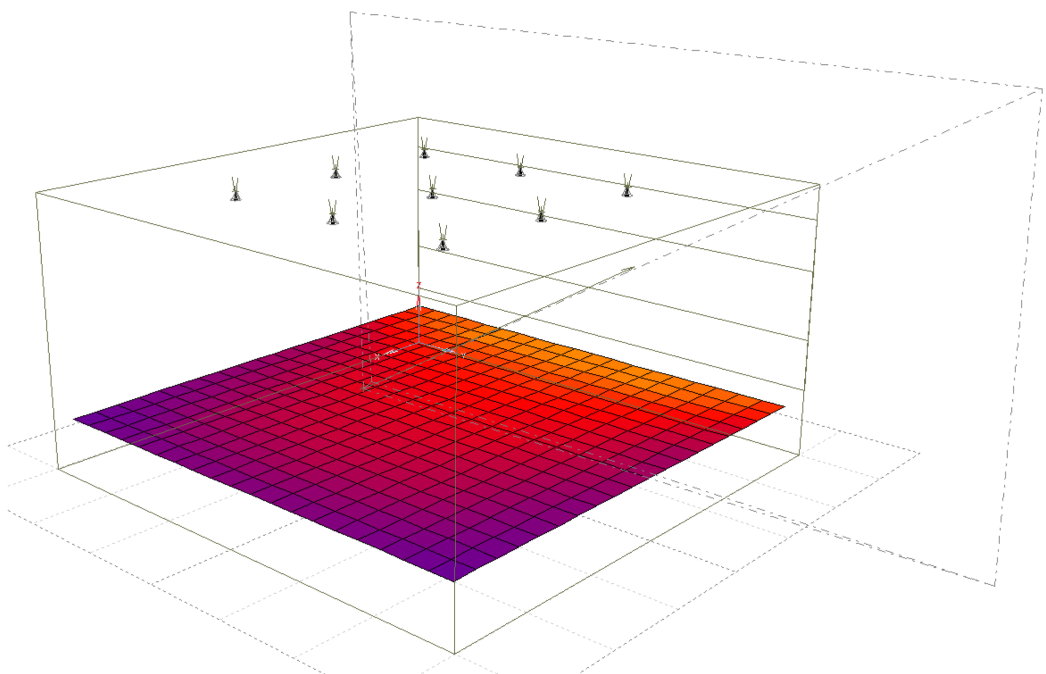


Figure 5 Schematic of visual simulation

In order to assess the quality of the indoor visual environment, two parameters should be considered, namely illumination level and illumination distribution. To obtain a comfortable indoor visual environment, the space lighting should be bright enough. At the same time the lighting level at a particular area cannot have a significant deviation with the surrounding area, or a glare would appear. According to above consideration, during the visual simulation both the illumination level on the 0.8 m height (which is a typical height of working desk) and the human sensitivity toward the glazing surface were simulated.

The window area serves as a connection between the occupant and the outdoor environment by the landscape view, which is considered quite important especially in high-rise cities such as Hong Kong. Since the proposed silica aerogel glazing was translucent, two different arrangements were considered in the simulation. The first arrangement was to completely replace the conventional glazing with the silica aerogel glazing. The second arrangement was to divide the glazing area into three parts, the upper part and the lower part were replaced by the silica aerogel glazing, while the middle part remained to be the conventional single clear glazing (since this part of glazing is the major area through which the occupant watch the outdoor environment). The schematic of the second arrangement is given below.

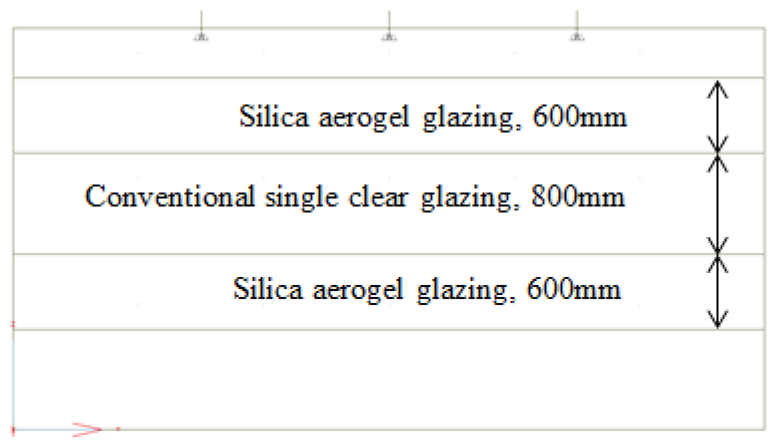


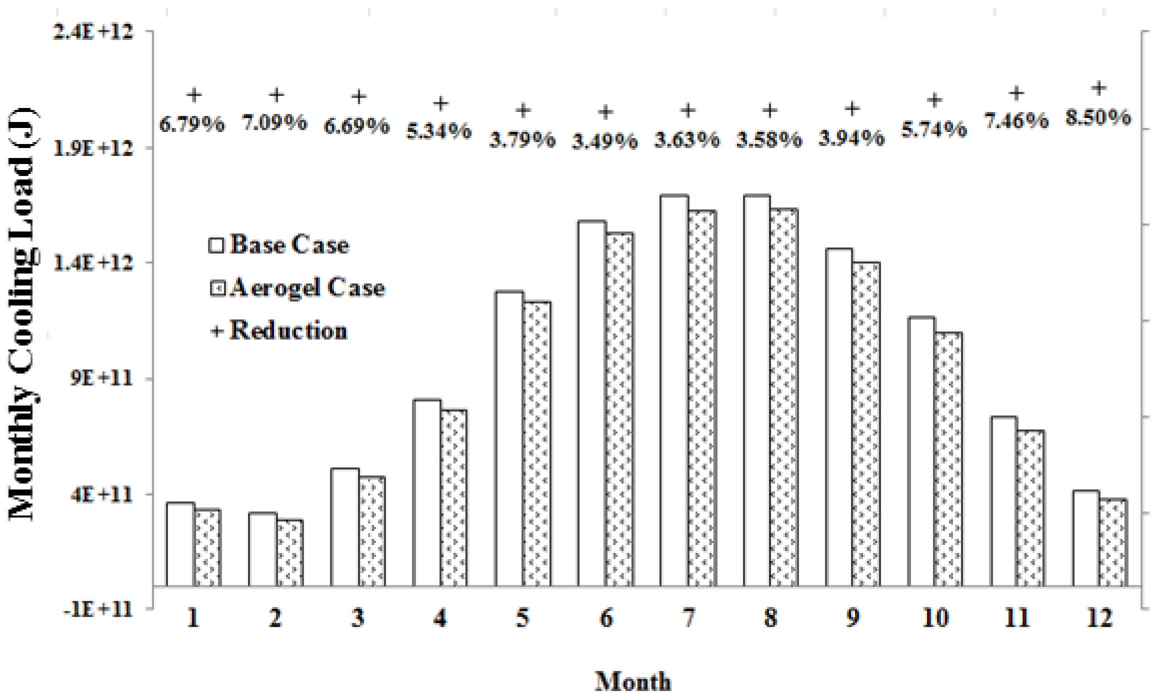
Figure 6 Schematic of the second arrangement

4. Result and discussion

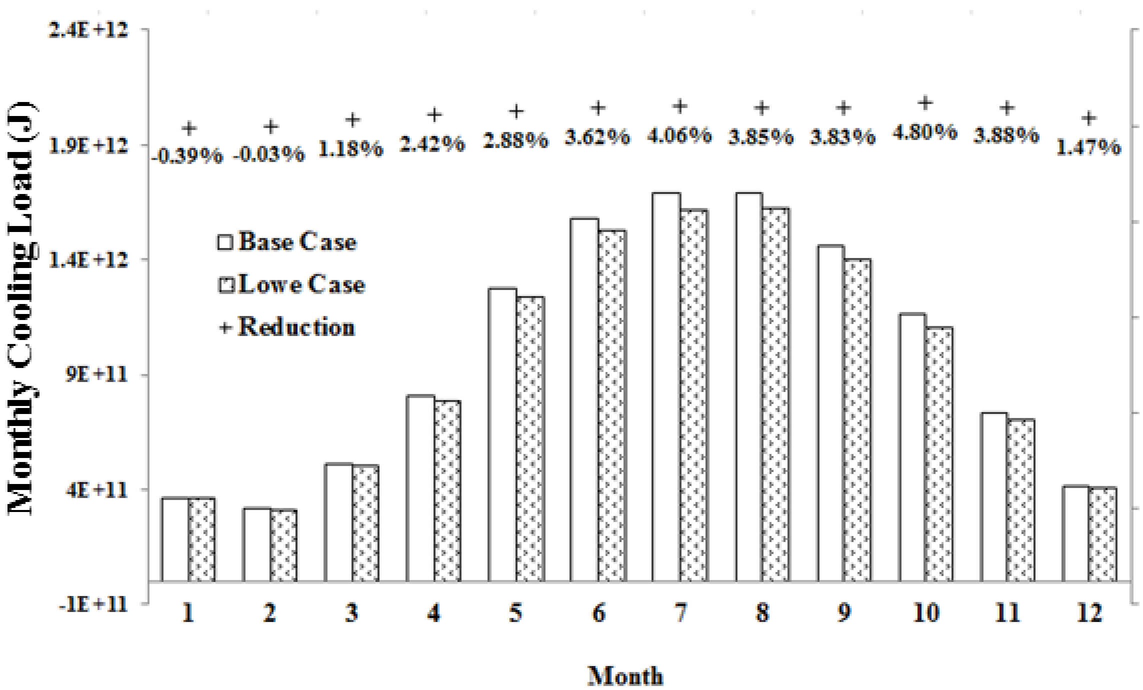
4.1. Thermal comfort analysis

4.1.1. Space temperature control strategy

Figure 7 gives the annual space cooling load inside the model building while setting the space temperature set point at 25℃. Base Case means the glazing used in this case was the glazing mentioned in Table 2. Aerogel Case means the glazing used in this case was the proposed silica aerogel glazing system. Lowe Case means the glazing used in this case was the low-e glazing described in Table 3.



A. Silica aerogel glazing



B. Low-e glazing

Figure 7 Annual space cooling load data while space temperature set point was 25℃

From Figure 7, if the space temperature was taken as the control object, the application of silica aerogel glazing system could reduce the annual space cooling load by 3.5% ~ 4%. It seemed that the cooling load reduction proportion was a bit low. The reason lies in the constitution of the cooling load in hot-humidity subtropical climate. Taking the cooling load in July as an example, Figure 8 presents the detailed breakdown of the space cooling load of Base Case simulation result in July. Clearly, in hot-humidity cities like Hong Kong, latent load accounts for a large part of the total space cooling load. In the hottest month, sensible load only took 53% of the total space cooling load, while the cooling load caused by envelope heat gain only took around 7% of the total cooling load. From this aspect, the application of the silica aerogel glazing could reduce the cooling load caused by envelope heat gain by around 50%, which was rather considerable.

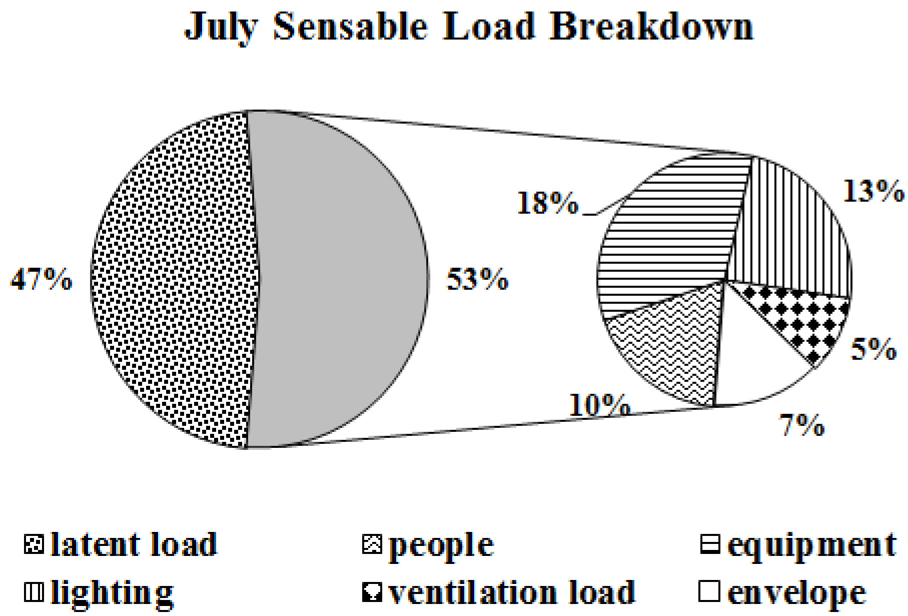
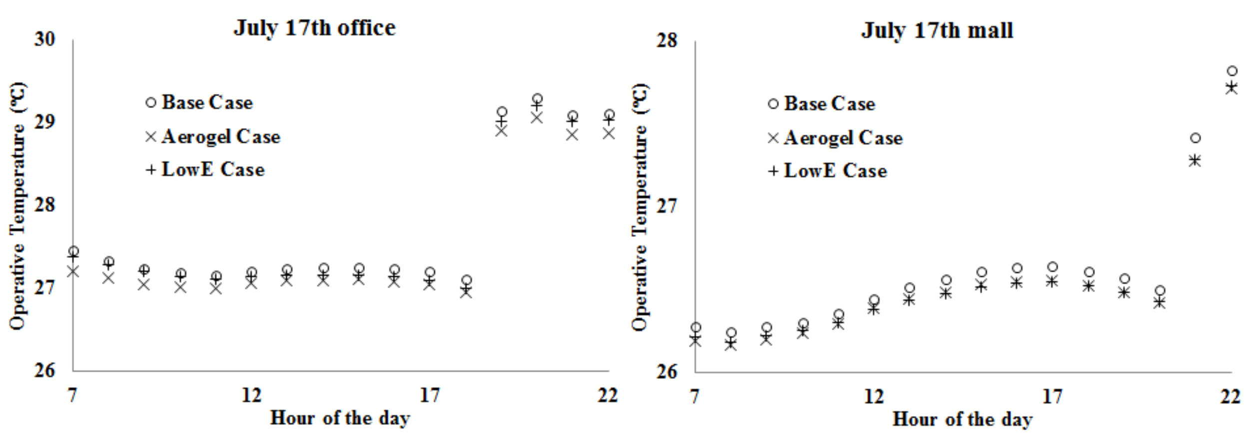
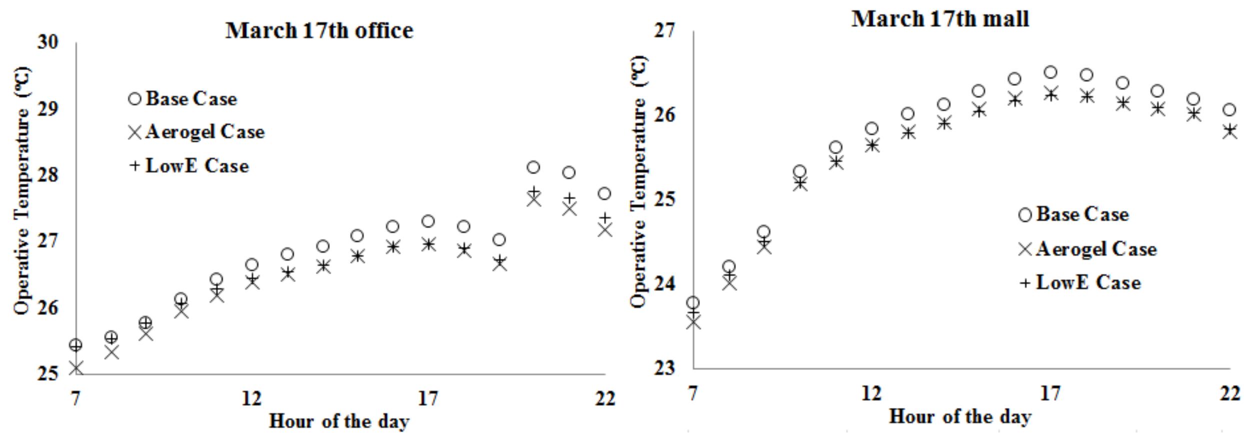


Figure 8 Detailed breakdown of space cooling load of Base Case in July

The energy performance of silica aerogel glazing system was slightly better than that of the low-e glazing selected. However, it should be noted that energy performance cannot reflect the glazing system's impact on thermal comfort. The indoor operative temperature and PMV data should be referred to describe the quality of the indoor thermal environment [41-45]. Since Hong Kong was located in cooling-dominant climate, only cooling situation should be considered all year round. One typical summer day (July 17th) and one typical transition season day (March 17th) were selected. The hourly operative temperature and PMV values in these two typical days are listed in Figure 9 and Figure 10.

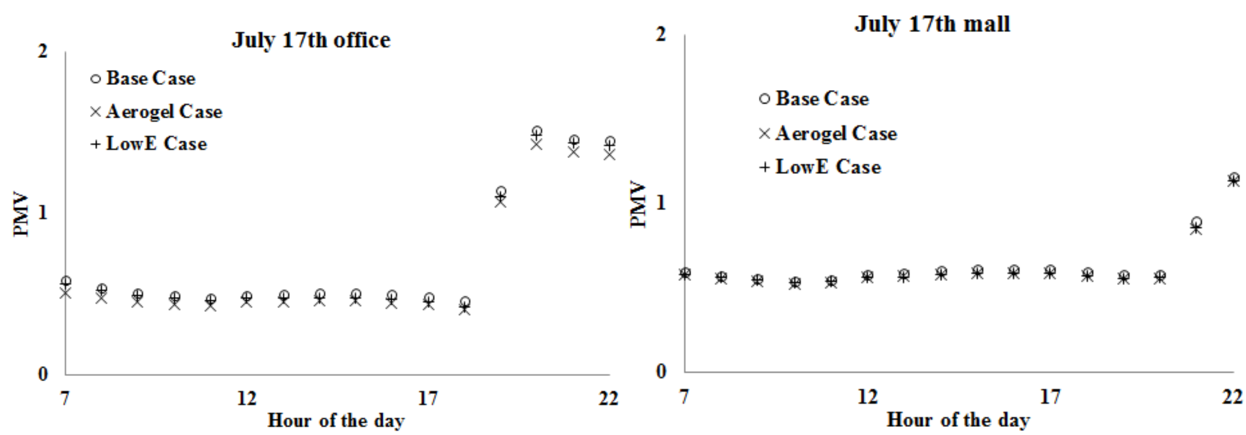


A. Operative temperature data on July 17th

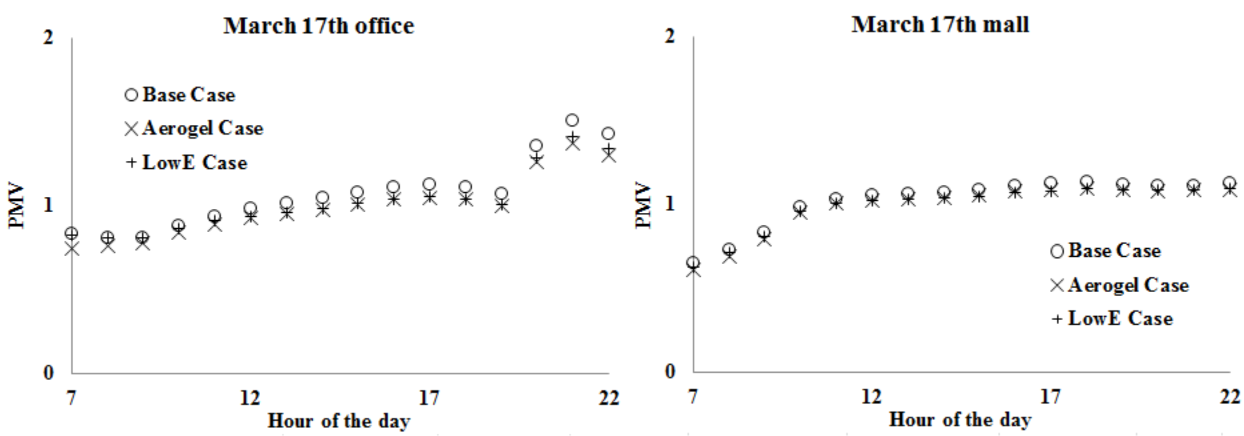


B. Operative temperature data on March 17th

Figure 9 Simulation result for operative temperature on two typical days



A. PMV data on July 17th



A. PMV data on March 17th

Figure 10 Simulation result for PMV on two typical days

Obviously, after equipped with the proposed silica aerogel glazing system, the indoor thermal comfort level was improved. From Figure 9 and Figure 10, it is clear that in Aerogel Case, the difference between operative temperature and space temperature got smaller. The PMV values were also closer to the comfort zone. The improvement in indoor thermal comfort is more obvious from Table 4 below.

Table 4 Thermal comfort status in different cases

Item		Base Case		Aerogel Case		LowE Case	
		Office area	Mall area	Office area	Mall area	Office area	Mall area
Average PMV	Annual	0.66	0.52	0.57	0.49	0.62	0.50
	Cooling season	1.11	0.78	1.01	0.75	1.02	0.75
	July	1.34	0.78	1.23	0.75	1.23	0.74
	August	1.15	0.76	1.05	0.73	1.05	0.72
Proportion of comfort period		34.37%	28.54%	38.34%	30.99%	37.74%	30.72%

In the office area, the proportion of thermally comfort period was increased by about 4%. While in the mall area, the proportion was increased by about 2.5%. On the annual basis, the silica aerogel glazing system performed the best among the three glazing system studied. Even in the hottest month, the performance of the silica aerogel glazing system retained almost equal to that of the selected low-e glazing.

However, it should be admitted first that choosing space temperature as the control object cannot maintain a stable indoor thermal environment. Judging from Figure 9, during summer, the operative temperature was always at least 1℃ higher than the space temperature. Even during the transition season, the operative temperature would be at least 1℃ higher than the space temperature for most time of the day. During some period the operative temperature could be almost 30℃. Judging from Figure 10, clearly the indoor thermal status was completely out of the occupant comfort zone the whole occupancy period. From Table 4, it can be further concluded that as the weather got hotter, the un-comfortable situation would get more serious.

4.1.2. Operative temperature control strategy

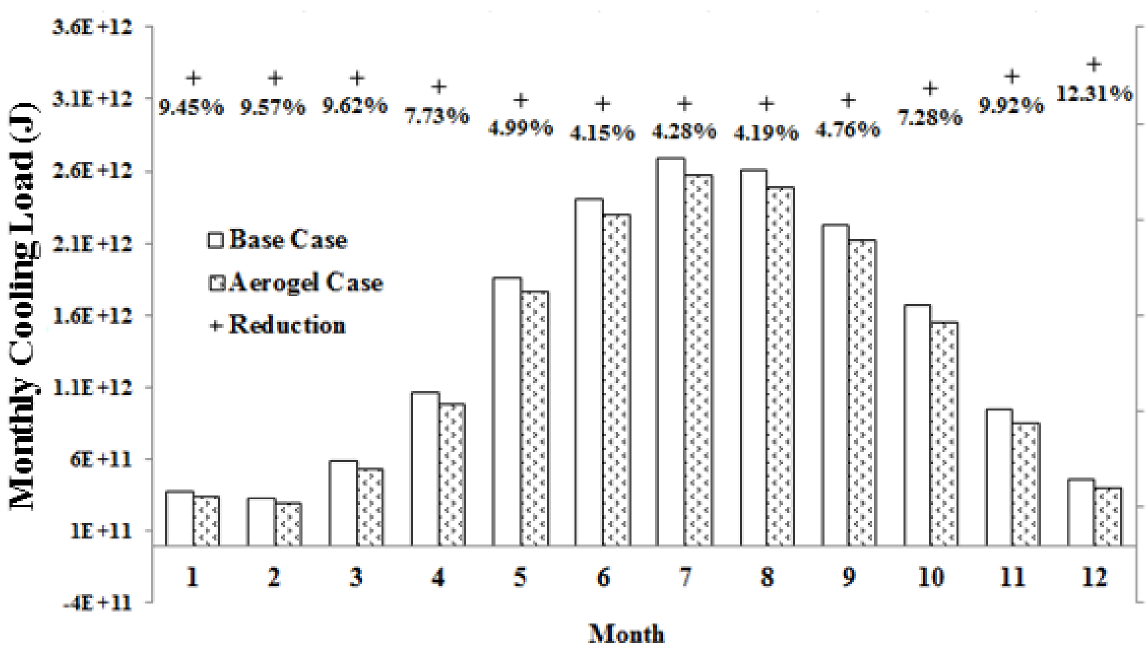
Table 5 presents the thermal comfort status inside the building while setting the operative temperature set point at 25℃.

Table 5 Thermal comfort status while operative temperature set point was 25℃

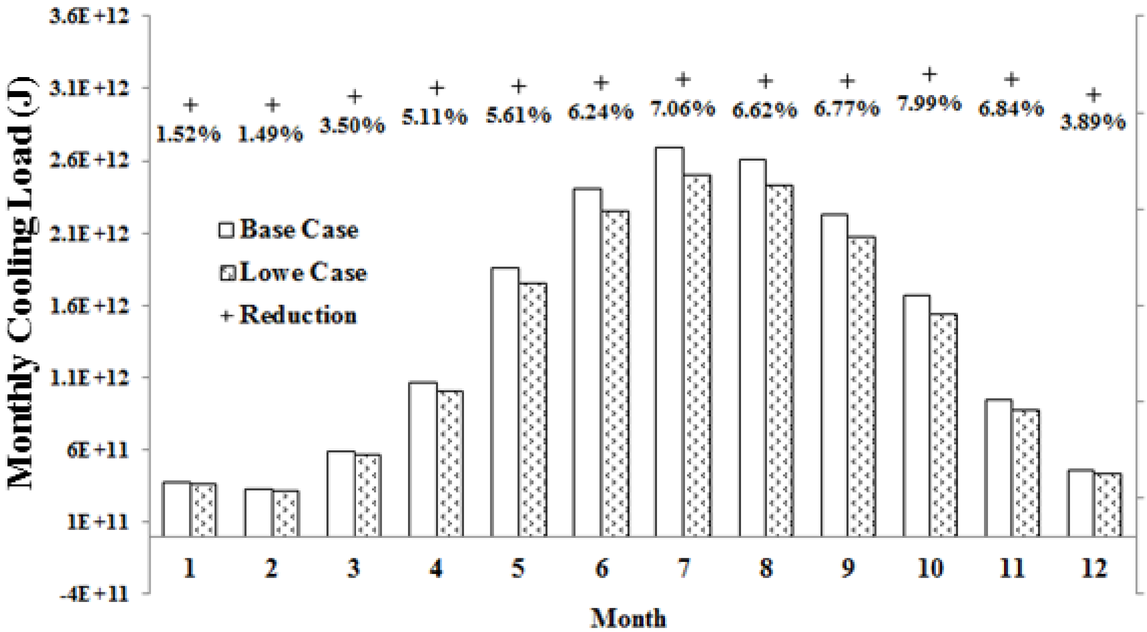
Item		Base Case		Aerogel Case		LowE Case	
		Office area	Mall area	Office area	Mall area	Office area	Mall area
Average PMV	Annual	-0.06	0.20	-0.07	0.19	-0.04	0.20
	Cooling season	-0.13	0.23	-0.13	0.23	-0.12	0.24
	July	-0.28	0.11	-0.27	0.11	-0.27	0.12
	August	-0.27	0.11	-0.26	0.12	-0.26	0.12
Proportion of comfort period		73.61%	68.82%	72.47%	69.55%	73.27%	69.47%

From the above presented simulation result, it is clear that while operative temperature was selected as the control object, the indoor thermal comfort status was improved significantly, the proportion of thermal comfort period rose from less than 40% to around 70%.

However, the improved thermal comfort level brought in more energy consumption, Figure 11 presents the annual cooling load inside the model building while setting the operative temperature set point at 25℃. Compared Figure 11 with Figure 6, it is obvious that though the application of silica aerogel glazing or low-e glazing could reduce the energy consumption by a considerable proportion, the energy consumed to maintain a more thermally comfortable environment was much higher than that when simply maintaining a fixed space temperature. Judging from Figure 7 and Figure 11, maintaining the operative temperature at 25℃ in July would generate a 2.69×10^{12} J space cooling load. The space cooling load would remain more than 2.5×10^{12} J even after silica aerogel glazing or low-e glazing was applied. While maintaining the space temperature at 25℃ in July would only generate a 1.69×10^{12} J space cooling load. This difference in energy consumption was shocking.



A. Silica aerogel glazing

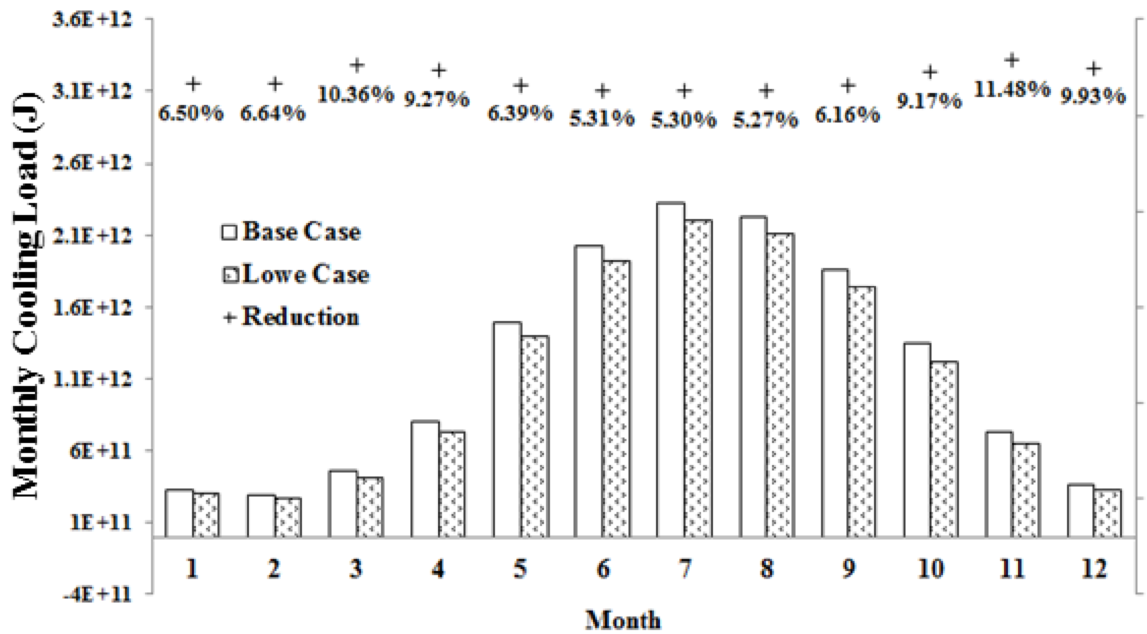


B. Low-e glazing

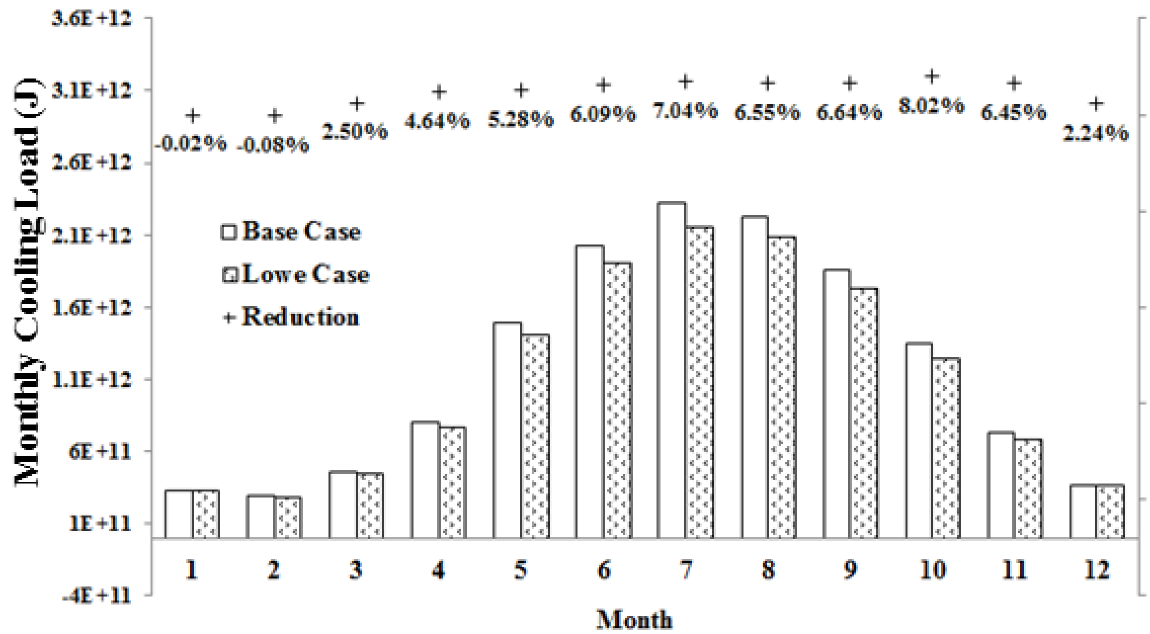
Figure 11 Annual space cooling load data while operative temperature set point was 25℃

Improvement should be made on the operative temperature control strategy, so that energy consumption could be reduced while still maintaining a satisfactory thermal comfort level. Analyzing the data in Table 5, it can be found that the average PMV values in office area were negative, which indicated that in many moments, the occupant felt "comfortably cold" (the PMV value was between 0 to -0.5). If the majority of PMV values can be controlled within 0 to 0.5, energy consumption can be reduced.

A series of cases were considered in the simulation analysis. An optimal operative temperature set point combination was obtained: 26℃ in office area and 25.5℃ in mall area. The annual space cooling load and the thermal comfort status were presented in Figure 12 and Table 6.



A. Silica aerogel glazing



B. Low-e glazing

Figure 12 Annual space cooling load data in the optimal operative temperature set point combination case

Table 6 Thermal comfort status in the optimal operative temperature set point combination case

Item	Base Case	Aerogel Case	LowE Case

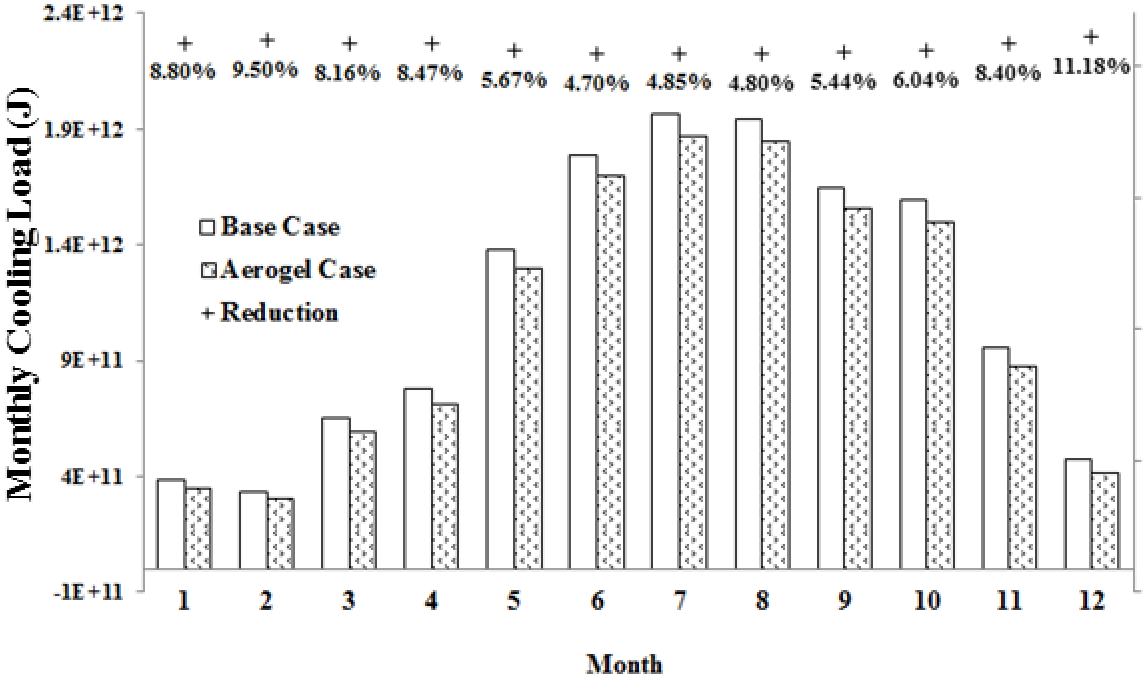
		Office area	Mall area	Office area	Mall area	Office area	Mall area
Average PMV	Annual	0.42	0.39	0.39	0.38	0.44	0.39
	Cooling season	0.55	0.53	0.56	0.53	0.56	0.53
	July	0.44	0.42	0.45	0.43	0.45	0.43
	August	0.45	0.43	0.46	0.44	0.46	0.44
Proportion of comfort period		80.80%	71.38%	81.01%	72.88%	80.53%	71.15%

From the simulation result of the optimal case, it is clear that compared with conventional single clear glazing system, the proposed silica aerogel glazing system could reduce a considerable proportion of energy consumption while still retaining a comfortable thermal environment in the model building. In the Base Case, the annual space cooling load was 1.42×10^{13} J. In the Aerogel Case the cooling load was 1.33×10^{13} J, a reduction of 7% could be expected. In the LowE Case, the cooling load was about 1.34×10^{13} J. With respect to the thermally comfortable period, both in the office area and mall area, the length of the periods were slightly improved compared with the Base Case. With reference to the simulation result of LowE Case, it can be concluded that the proposed silica aerogel glazing system performed almost equally well as the selected low-e glazing.

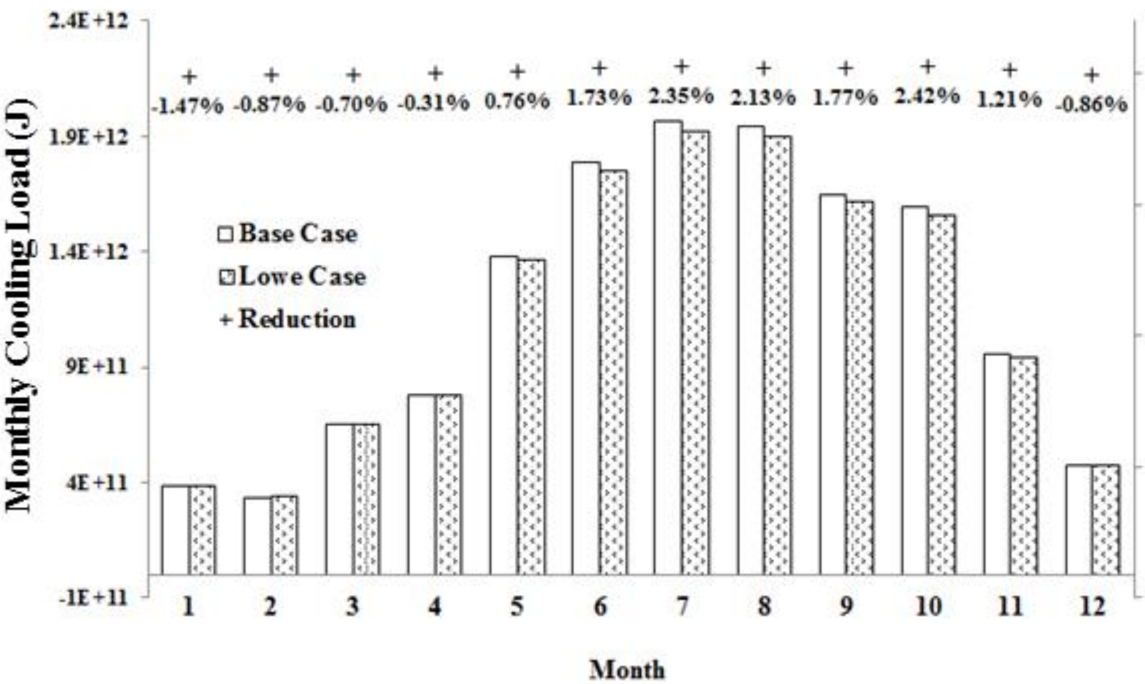
4.1.3. PMV control strategy

Besides the space temperature control and operative temperature control strategies, there is another control strategy which directly take occupant's PMV value as the control object. The PMV control strategy was the most extreme control strategy. This strategy can ensure that within the whole occupancy period, the occupant would feel thermally comfortable. Figure 13 gives the annual space cooling load while the indoor PMV was controlled within 0~0.5 (which was defined as the comfort zone).

First it is obvious that under PMV control strategy, the application of silica aerogel glazing could reduce the space cooling load significantly. In the Base Case the annual space cooling load was around 1.39×10^{13} J, while in the Aerogel Case the value was 1.30×10^{13} J. The reduction was 6.5%. Second, it should be noticed that under the PMV control strategy, the performance of the silica aerogel glazing is notably better than that of the low-e glazing. Compared Figure 13 with Figure 11 and Figure 12, it is obvious that as the request of thermal comfort got stricter, the adaptability of the silica aerogel glazing is better.



A. Silica aerogel glazing

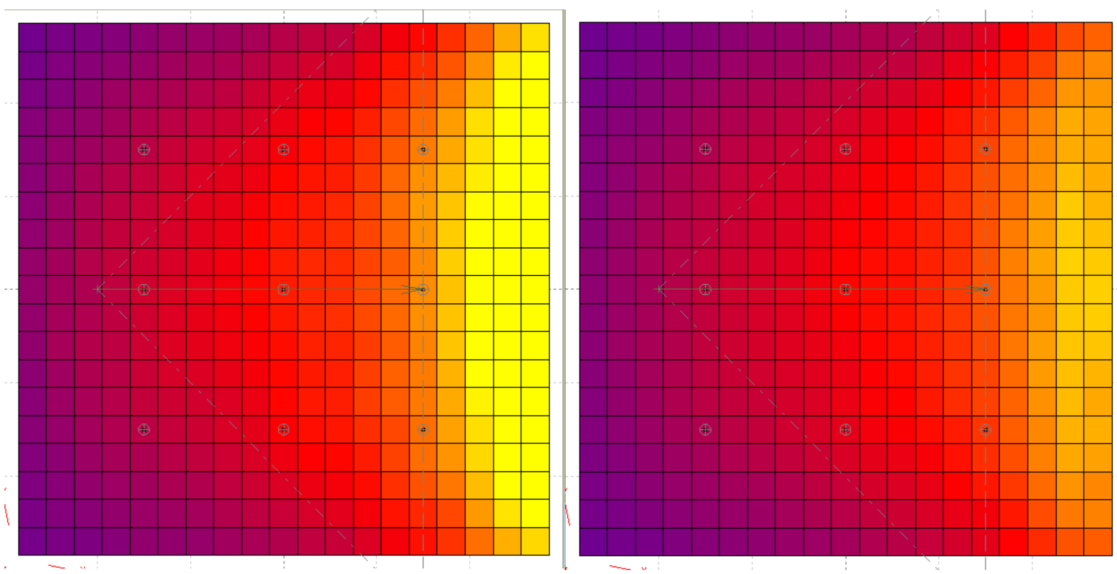


B. Low-e glazing

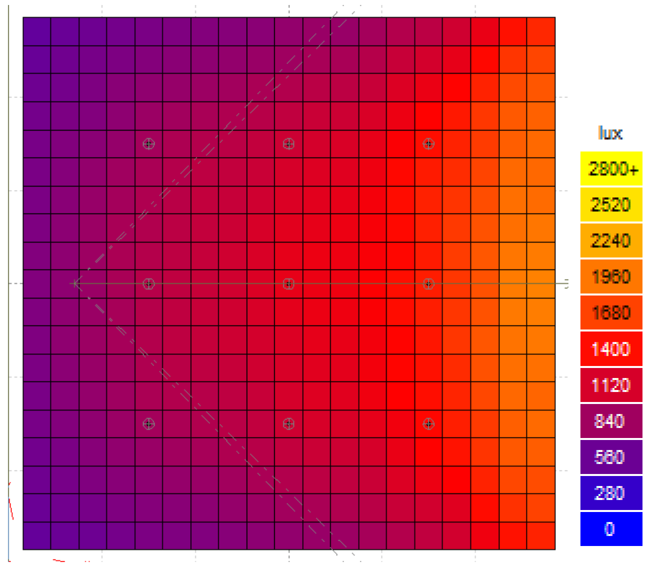
Figure 13 Annual space cooling load data while the occupant's PMV was within 0~0.5

4.2. Visual comfort analysis

The proposed silica aerogel glazing was translucent, and the transmittance was lower than that of the single clear glazing. The application of the silica aerogel glazing would reduce the indoor illumination level and block the indoor view to the outside environment, as shown in Figure 2. However, the optical features of the silica aerogel glazing could help reduce the influence of glare on indoor visual comfort and make the indoor illumination level more uniformly. Thus during the visual comfort simulation, the focus was to test whether the proposed silica aerogel glazing could eliminate the glare while still retaining an acceptable indoor illumination level. Three most unfavorable cases were selected to assess the visual performance of the proposed silica aerogel glazing: an east facing office at 8am, July 17th, a south facing office at 12am, July 17th, and a west facing office at 5pm, July 17th. Figure 14-16 presents the indoor illumination level in different cases. In the following figures and discussion, Base Case means the glazing used in this case was the glazing mentioned in Table 2. Combination Case means the arrangement described in Figure 6 was applied in the case. Aerogel Case means the glazing used in this case was the proposed silica aerogel glazing system.

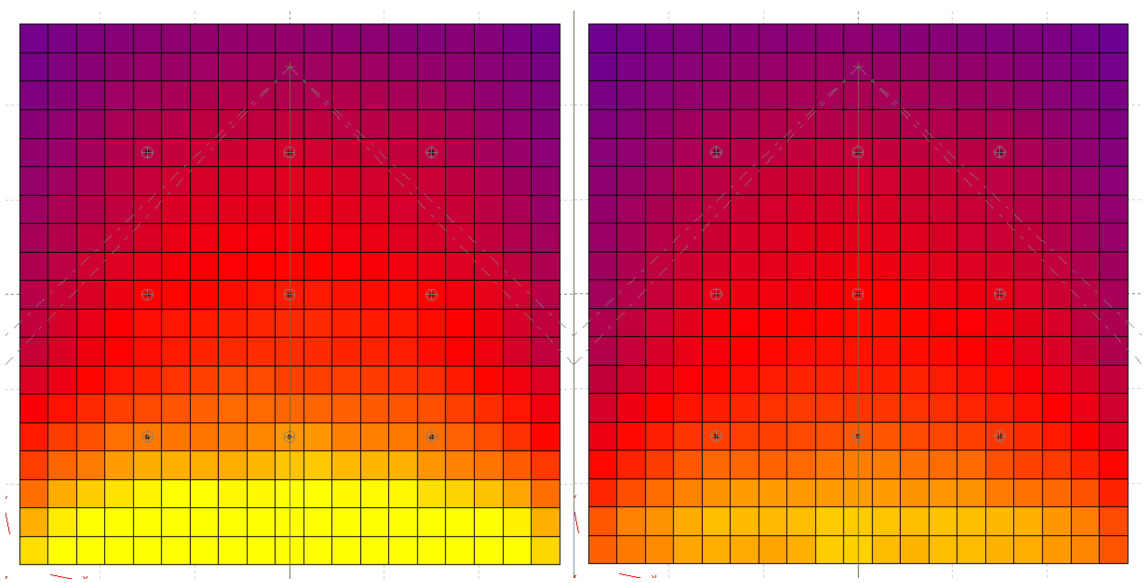


A. Base Case **B. Combination Case**

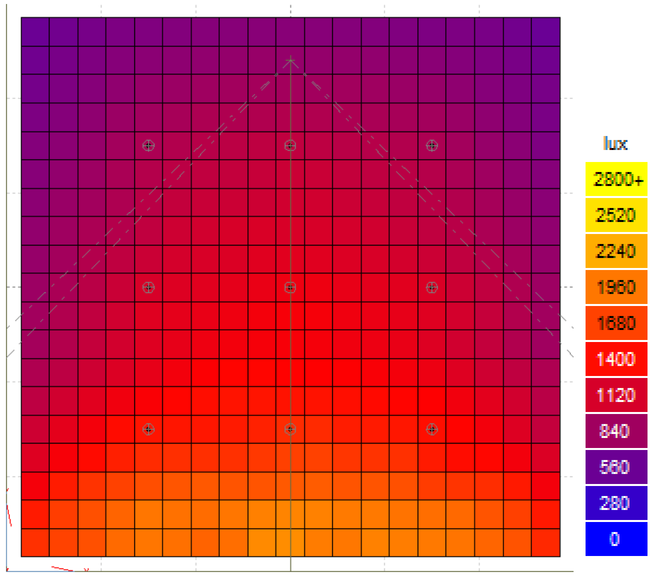


C. Aerogel Case

Figure 14 Indoor illumination level in an east facing office at 8am, July 17th

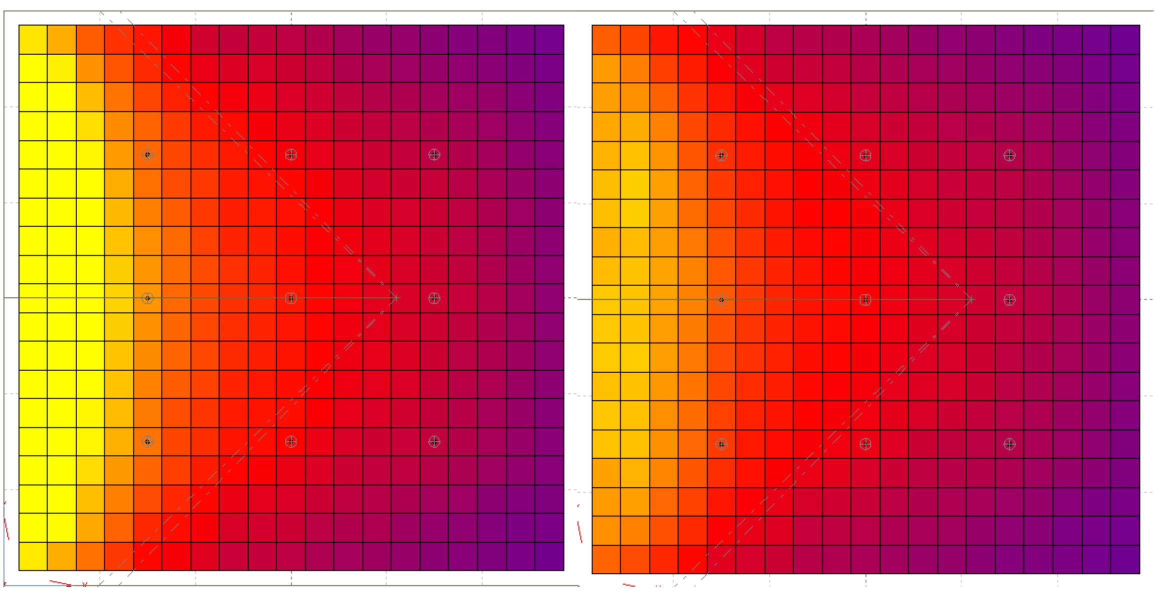


A. Base Case **B. Combination Case**

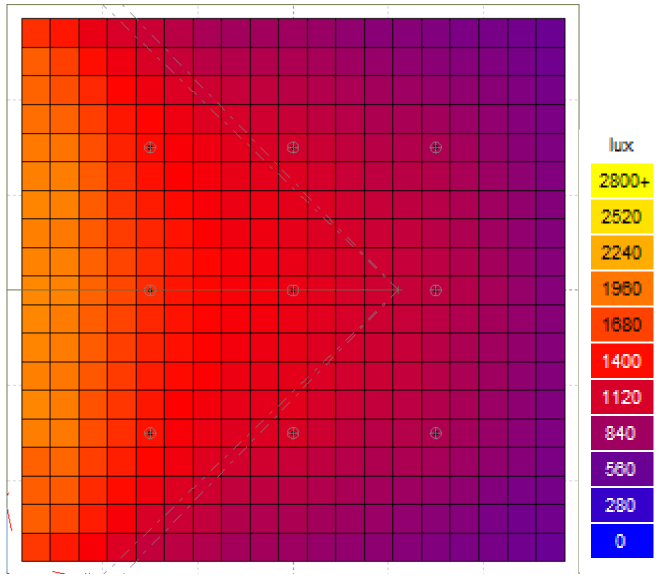


C. Aerogel Case

Figure 15 Indoor illumination level in a south facing office at 12am, July 17th



A. Base Case **B. Combination Case**

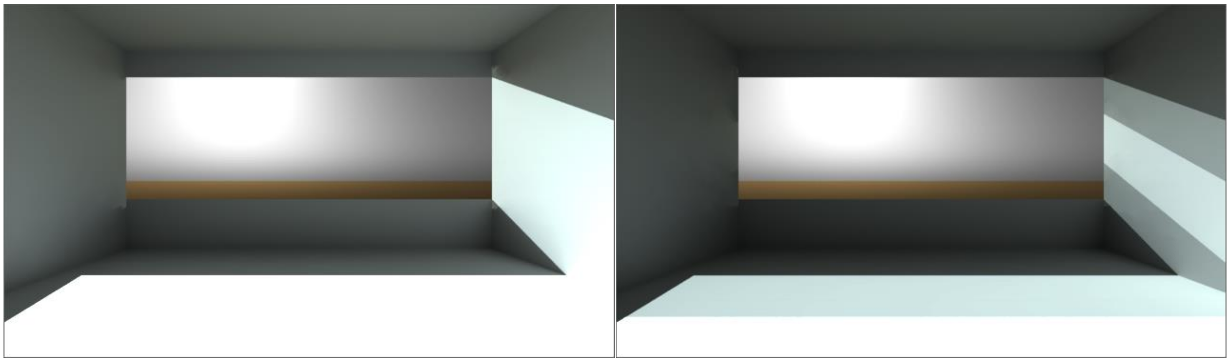


C. Aerogel Case

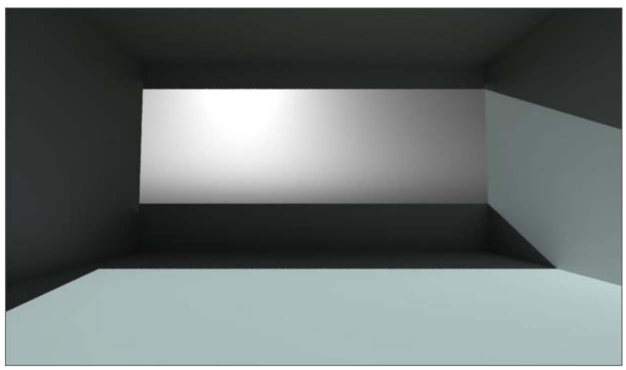
Figure 16 Indoor illumination level in a west facing office at 5pm, July 17th

From Figure 14 -16, it is clear that the bright zone near the window area was significantly weakened, which indicated that the lighting quality on the working pane was highly improved. Also, it is obvious that though the application of silica aerogel glazing caused a drop of indoor illumination level, especially in the near window area, the overall illumination level within the office was still satisfactory. The illumination level was above 500 lux at all the spots calculated. The spots with an illumination level of less than 840 lux still existed in the corners that were far away from the window. In the Semi-Aerogel Cases, the illumination distribution of the office's inner part barely changed. In the Aerogel Cases, the area in which the illumination level was less than 840 lux increased slightly, but the overall illumination level could still meet the requirement.

Figure 17 -19 display the simulation result of the human sensitivity toward the glazing surface in different cases. From the simulation result it is clear that with the application of silica aerogel glazing, the glare appeared on glazing surface was suppressed. The area of glare was reduced, the brightness also decreased. It should be especially noted that at the moment displayed in Figure 18, the solar elevation angle was quite high, thus the majority of solar radiation projected on glazing area was the indirect solar radiation of the sky. It could be observed that the silica aerogel glazing performed perfectly well toward the large amount of indirect solar radiation. The dazzling glazing surface completely eased up. The occupant could directly look at the glazing surface, which is particularly important since the glazing area took a large proportion of the wall surface.

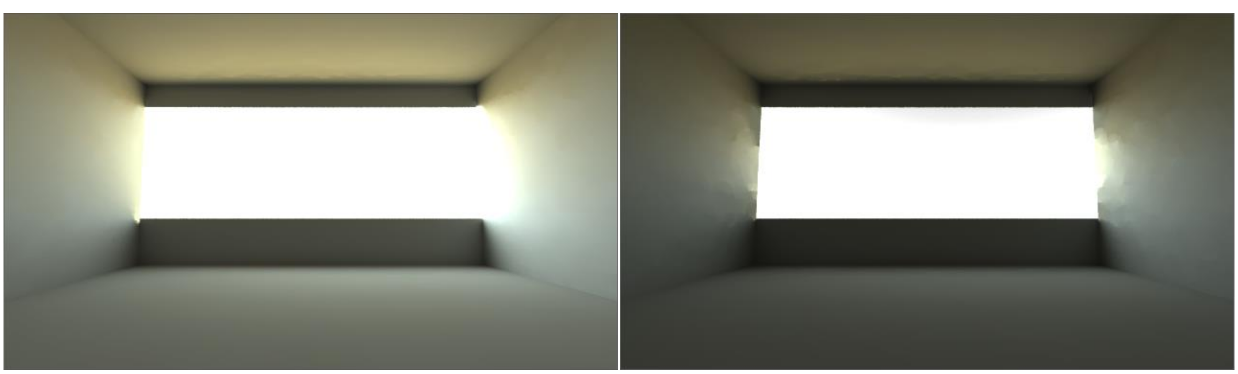


A. Base Case **B. Combination Case**

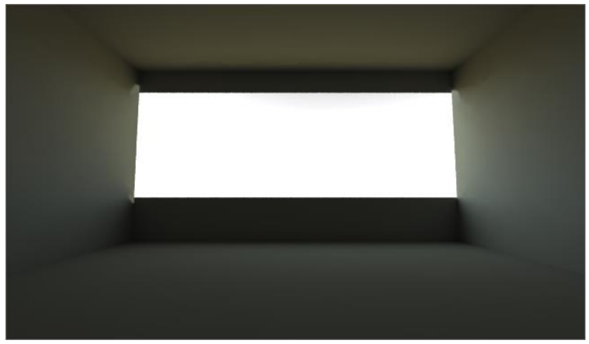


C. Aerogel Case

Figure 17 Human sensitivity toward window in a west facing office at 5pm July 17th

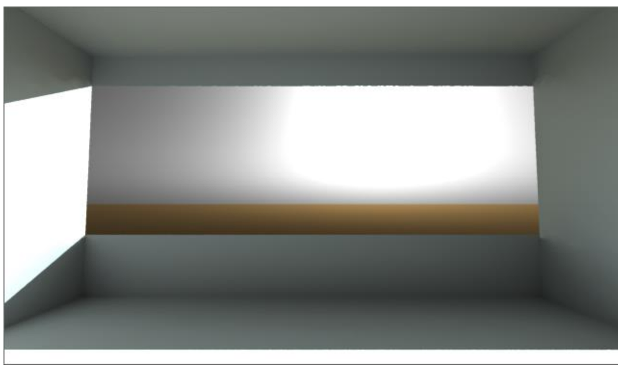


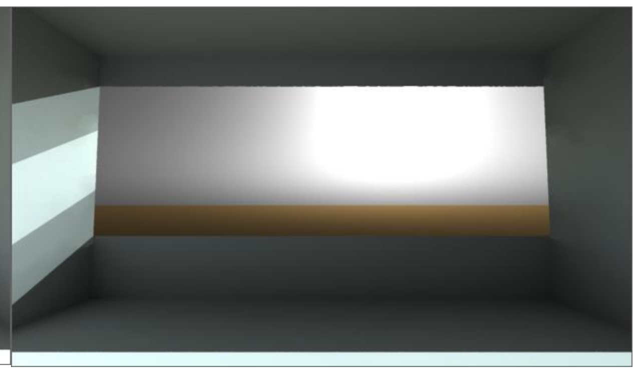
A. Base Case **B. Combination Case**



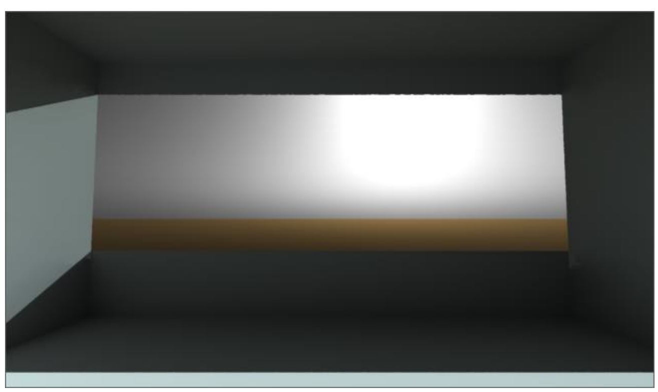
C. Aerogel Case

Figure 18 Human sensitivity toward window in a south facing office at 12am, July 17th





A. Base Case **B. Combination Case**



C. Aerogel Case

Figure 19 Human sensitivity toward window in a west facing office at 5am, July 17th

The combination of conventional single clear glazing and the proposed silica aerogel glazing showed a satisfactory performance, which reflected a possibility of improving indoor visual environment while still retaining a pleasant outdoor view. In order to simulate the occupant's visual effect toward the outside view when the upper and lower part of the window was replaced by the silica aerogel glazing, a visual rendering program named vray was applied. Figure 20 displays the simulation result of the change in vision before and after the application of the silica aerogel glazing.

Figure 20 View comparison: Before and after the silica aerogel glazing application

Daylight is considered the best light source for human being, a proper exposure to daylight could significantly improve the working efficiency [46]. The open view through windows is considered as a highly desirable feature for office building especially in high-rise cities. The application of silica aerogel glazing system could reduce the influence of glare on the indoor visual environment effectively. The combination of the silica aerogel glazing and conventional single clear glazing could improve the visual comfort level while still retain a pleasant outdoor view.

5. Conclusion

This paper describes a simulation work conducted on a silica aerogel glazing system. The performance of the proposed glazing system on indoor environment quality (IEQ) control in cooling-dominant subtropical climate was analyzed from two aspects: thermal and visual comfort. A typical commercial building in Hong Kong was selected as a case study. The following conclusions were achieved.

1. The application of the silica aerogel glazing can achieve a better indoor thermal comfort level compared with common-used conventional single clear glazing system in subtropical climate.

- While taking space temperature as the control object, the silica aerogel glazing could keep the indoor thermal environment thermally comfortable for a longer period.
- To maintain an equal indoor thermal comfort level, the silica aerogel glazing could cause an at least 4% reduction in space cooling load. A widely used shading type low-e glazing was also analyzed in the simulation. The simulation result indicated that the performance of the proposed silica aerogel glazing is almost equal to that of the low-e glazing.
- While the indoor environment had a stricter requirement for indoor thermal comfort, the practicality of the silica aerogel glazing was better.

2. The silica aerogel glazing also can retain a pleasant indoor visual environment.

- Though the visible daylight was reduced, the indoor illumination level was still above the limit.
- The bright zone in the near window area was significantly weakened.
- The glare appeared on glazing surface was also undermined.
- The combination of the conventional single clear glazing and the silica aerogel glazing showed a strong adaptability, which indicated a possible mode for the silica aerogel glazing application.

In the future research, an on-site measurement will be conducted, so that the applicability of the silica aerogel glazing can be further tested.

Acknowledgement

The work described in this paper was financially supported by the Research Grants Council of Hong Kong (Project no. 522613).

7. Reference

[1] U. S. Green Building Council, LEED 2009 rating system review: Indoor Environmental Quality. 2009.

[2] Green Building Council Australia, Introducing Green Star, 2014.

[3] Hong Kong Green Building Council, Hong Kong Beam Society, BEAM Plus for New Buildings, Version 1.1, 2010.

[4] Kwangho Kim, Byungseon Sean Kim , Sanghyun Park, Analysis of design approaches to improve the comfort level of a small glazed-envelope building during summer, Solar Energy, 81(2007) 39-51.

[5] G.F. Menzies, J.R. Wherrett, Windows in the workplace: examining issues of environmental sustainability and occupant comfort in the selection of multi-glazed windows, Energy and Buildings, 37 (2005) 623–630.

[6] Pablo La Roche, Murray Milne, Effects of window size and thermal mass on building comfort using an intelligent ventilation controller, Solar Energy, 77(2004) 421-434.

[7] Somsak Chaiyapinunta, Bunyarit Phueakphongsuriya, Khemmachart Mongkornsaksit, Nopparat Khomporn, Performance rating of glass windows and glass windows with films in aspect of thermal comfort and heat transmission, Energy and Buildings, 37 (2005) 725–738.

[8] A. Stegou-Sagia , K. Antonopoulos, C. Angelopoulou, G. Kotsiovelos, The impact of glazing on energy consumption and comfort, Energy Conversion and Management, 48 (2007) 2844–2852.

[9] M.C. Singh, S.N. Garga, Ranjna Jha, Different glazing systems and their impact on human thermal comfort—Indian scenario, Building and Environment, 43(2008) 1596-1602.

[10] Ruey-Lung Hwang, Shiu-Ya Shu, Building envelope regulations on thermal comfort in glass facade buildings and energy-saving potential for PMV-based comfort control, Building and Environment, 46(2011) 824-834.

[11] Jian Yao, Neng Zhu, Evaluation of indoor thermal environmental, energy and daylighting performance of thermotropic windows, Building and Environment, 49(2012) 283-290.

[12] Valentina Serra, Fabio Zanghirella, Marco Perino, Experimental evaluation of a climate fac¸ade: Energy efficiency and thermal comfort performance, Energy and Buildings, 42(2010) 50-62.

[13] Francesco Goia, Marco Perino, Valentina Serra, Improving thermal comfort conditions by means of PCM glazing systems, Energy and Buildings, 60(2013) 442-452.

[14] A. Tzempelikos, M. Bessoudo, A.K. Athienitis, R. Zmeureanu, Indoor thermal environmental conditions near glazed facades with shading devices - Part II: Thermal comfort simulation and impact of glazing and shading properties, Building and Environment, 45(2010) 2517-2525.

[15] G.M. Stavrakakis, P.L. Zervas, H. Sarimveis, N.C. Markatos, Optimization of window-openings design for thermal comfort in naturally ventilated buildings, Applied Mathematical Modelling, 36(2012) 193-211.

[16] Francesca Cappelletti, Alessandro Prada, Piercarlo Romagnoni, Andrea Gasparella, Passive performance of glazed components in heating and cooling of an open-space office under controlled indoor thermal comfort, Building and Environment, 72(2014) 131-144.

[17] Carlos Ernesto Ochoa, Isaac Guedi Capeluto, Evaluating visual comfort and performance of three natural lighting systems for deep office buildings in highly luminous climates, Building and Environment. 41(2006) 1128–1135.

[18] Anca D. Galasiu, Morad R. Atif, Robert A. MacDonald, Impact of window blinds on daylight-linked dimming and automatic on/off lighting controls, Solar Energy 76(2004) 523–544.

[19] A. K. Athienitis, A. Tzempelikos, A methodology for simulation of daylight room illuminance distribution and light dimming for a room with a controlled shading device, Solar Energy. 72(2002) 271-281.

[20] Ji-Hyun Kim, Young-Joon Park, Myoung-Souk Yeo, Kwang-Woo Kim, An experimental study on the environmental performance of the automated blind in summer, Building and Environment. 44(2009) 1517–1527.

[21] E.S. Leea, A.Tavil, Energy and visual comfort performance of electrochromic windows with overhangs, Building and Environment, 42(2007) 243-244.

[22] Carlos Ernesto Ochoa, Isaac Guedi Capeluto, Advice tool for early design stages of intelligent facades based on energy and visual comfort approach, Energy and Buildings, 41(2009) 480-488.

[23] Carlos E. Ochoa, Myriam B.C. Aries, Evert J. van Loenen, Jan L.M. Hensen, Considerations on design optimization criteria for windows providing low energy consumption and high visual comfort, Applied Energy, 95(2012) 238-245.

[24] Alessandro Cannavalea, Francesco Fiorito, Debora Resta, Giuseppe Gigli, Visual comfort assessment of smart photovoltachromic windows, Energy and Buildings, 65 (2013) 137–145.

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

[26] 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.

[27] 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.

[28] 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.

[29] 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.

[30] 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.

[31] 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.

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

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

[34] 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.

[35] 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.

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

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

[38] Franco Cotana, Anna Laura Pisello, Elisa Moretti, Cinzia Buratti, Multipurpose characterization of glazing systems with silica aerogel: In-field experimental analysis of thermal-energy, lighting and acoustic performance, Building and Environment, 81(2014) 92-102.

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

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

[41] Niu, Jianlei, and John Burnett. "TECHNICAL PAPERS-4200-Integrating Radiant/Operative Temperature Controls into Building Energy Simulations." ASHRAE Transactions-American Society of Heating Refrigerating Airconditioning Engin 104.2 (1998): 210-217.

[42] M. Soleimani-Mohseni, B. Thomas, Per Fahlen, Estimation of operative temperature in buildings using artificial neural networks. Energy and Buildings, 38(2006) 635-640.

[43] Kwok Wai Horace Mui, Wai Tin Daniel Chan. Adaptive comfort temperature model of air-conditioned building in Hong Kong. Building and Environment, 38(2003) 837-852.

[44] K. W. Mui, L. T. Wong, Neutral temperature in subtropical climates- A field survey in air-conditioned offices. Building and Environment, 42(2007) 699-706.

[45] Stefano Paolo Corgnati, Enrico Fabrizio, Marco Filippi. The impact of indoor thermal conditions, system controls and building types on the building energy demand. Energy and Buildings, 40(2008) 627-636.

[46] Danny H.W. Li, Joseph C. Lam, Evaluation of lighting performance in office buildings with daylighting controls, Energy and Buildings. 33(2001) 793-803.