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Comprehensive Analysis on Thermal and Daylighting Performance of Low-E Glazing and Shading Designs on Office Building Envelope in Cooling-Dominant Climates

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Abstract: Conducting energy-efficient designs on building window can be a solution to relieving the pressure caused by growing building energy consumption. In this paper, a series of simulation studies were carried out to evaluate the performance of several popular energy-efficient window designs in cooling-dominant climates. Both thermal and daylighting performance were considered during the analysis. Results indicate that among all designs studied, low-e glazing achieves a best performance, while double-layer glazing performs the worst. Energy-efficient designs on the east and west orientations are the most cost-effective in cooling-dominant climates. As latitude rises, the performance of window designs on the south orientation is getting better. It is also discovered that only in area very close to equator performance of north facing window designs is satisfactory. Furthermore, as the reflectivity of blind louver decreases, both thermal and daylighting performances drop.

Keywords: shading design, low-e glazing, building envelope, energy-efficient design, solar heat gain

Introduction

Window provides the occupants with a connection to the outside environment. The open view through windows is considered as a highly desirable feature for office building especially in high-rise cities. Glazing area is a key factor being noticed in building energy consumption. Windows also provides daylighting, which helps to reduce energy consumption from artificial lighting system as well as air-conditioning load. However, at the same time large

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window area can also lead to a large amount of unwanted solar radiation heat gain. Achieving a balance between letting in daylight and blocking out solar heat gain is a major challenge..

The US government proposed a project named "Green Light Program" in 1991, with the purpose to promote the development of efficient lighting and to control the lighting electricity. Policies such as fiscal subsidies and time-of-use price were also carried out. It was believed that proper daylighting design can largely reduce the building energy consumption, and the vision efficiency could also be improved at the same time [2, 3].

Li & Tsang carried out detailed studies on key building parameters affecting the daylighting designs, and found out that daylighting performance in office buildings as well as school buildings could be quite effective, in which situation about 25% of the total electric lighting energy consumption could be saved. It was also found that the scale of the room and the shading option could largely affect the daylighting performance of the buildings. These basic researches laid a solid foundation for further investigations [4].

Window openings provide the space near it a satisfying daylighting level, but the day lighting level deep in the room may not always be desirable. In order to fulfill the minimum requirement of visual environment, an artificial lighting system is needed. Early studies mainly focus on the simulation of energy saving from the artificial lighting dimming as a function of the daylighting availability. Bodart & Herde developed a calculation model to predict the energy consumption of the interaction of daylighting and artificial lighting system. They argued that only considering the quantity of daylight, artificial lighting energy consumption could be reduced by 50%~80% [5]. Li et al. discovered that with the application of high frequency dimming control of daylighting equipment, the artificial lighting energy consumption could be reduced by more than 30% [3]. They also discovered that utilizing energy-efficient light fitting with dimming control and proper daylighting schemes, the energy consumption could be further cut. The performances of two basic categories of photoelectric lighting controls: the on-off control and the dimming control were also discussed. It was believed that when it came to brightness of the working plane, the daylight availability is the key parameter to estimate the energy saving under on-off and dimming controls, as the daylight availability decreases, the dimming control acts efficiently, but when it was in a high level, the on-off control turned out to be better performing [6].

As the awareness of daylighting getting popular, various sorts of daylighting equipment have been manufactured. The application of advanced daylighting equipment is expected to reduce solar heat gain while improve the comfort level. The number of studies on these daylighting devices is large. Table 1 gives a summary of representative researches on the topic.

Table 1 Summary of literature review result on energy saving potential of advanced daylighting equipment in buildings

Authors	Concern addressed	Methodology	Conclusion
Galasiu & Atif	The impact of window blinds on two photocontrolled lighting system: continuous dimming and automatic on/off.	On-site measurement in two side-by-side offices. Lighting energy consumption was recorded from 6 AM to 6PM for a year	Daylighting can reduce 50%~60% of lighting energy consumption in the building. Window blind would largely reduce the energy saving due to daylighting. Of the two photocontrolled lighting system studied, automatic on/off system achieves a greater saving [7].
Athienitis & Tzempelikos	To develop a methodology for simulation of office equipped with motorized reflective blind in between double-layer glazing.	An experiment is conducted to achieve the daylight transmittance equations of the window system as a function of sky condition. A simulation is then processed to determine the energy saving from the system	The lighting energy saving from this window system could be more than 75% in overcast days and even 90% for clear days. Meanwhile, proper control of blinds can avoid glare. However, frequent movement of blinds should be prevented [8].
Chaiwiwatworakul et al.	The performance of automated blind cooperation with dimming controlled artificial lighting system in tropical region.	An experiment was conducted in a test building. a dimming controller was installed in the lighting system. Indoor illumination level as well as lighting energy consumption was measured.	The application of step-less controlled blind can result in a lighting energy saving of up to 80%. At the same time, the indoor visual environment can also be improved [9].
Lee & Selkowitz	The lighting energy saving potential of two different daylighting control system on automated rolling shades.	A 9-month monitored field study was carried out in a 401 m2 unoccupied mockup. . Indoor illumination level as well as lighting energy consumption was measured.	Work plane illumination level can be maintained for over 95% of the monitored period. A lighting energy saving of 5-10% and 25-40% can be achieved for dimming control and DALI-based control, respectively [10].
Kim et al.	The lighting energy saving ability of automated blind and the insufficiency of the control algorithm.	A survey is first conducted to collect the blind use pattern. With the operation data two control patterns were developed to apply in the experiment. The temperatures in test rooms with no air-conditioning were tested.	The automated blind can reduce the room temperature by around 2~3℃ while no air-conditioning is applied. However, when it comes to thermal comfort, automated blind performs worse than manual blinds [11].

Inoue	The impact of automatic response dimming glass on the air-conditioning load.	Several window systems with the combination of rhermotropic glass, low-e glass, air gap and phase-change materials were prepared and measured in a building with no HVAC system. the indoor temperature was recorded. A series of simulation works were also conducted.	A reduction of at least 20% can be expected from air-conditioning energy consumption. The indoor visual environment is also improved [12].
Li et al.	The impacts of the solar film coating on cooling energy requirements and electric lighting loads.	A field measurement in an office building was arranged. The solar radiation heat, indoor illumination level and energy consumption were recorded.	A 30% decline in solar radiation heat gain is observed. The electric lighting energy saving depends largely on the amount of diffuse radiation. Also, the performance of solar film coating depends largely on the building shape and type of HVAC system [13]
Ghisia & Tinker	The practicality of advanced daylighting equipment with the application of fiber optics in Brazil and the UK.	A methodology is first developed to calculate the lighting energy saving from the illumination level. Then a large number of simulation is carried out to get the daylighting effect of fiber optics.	With the application of fiber optics daylighting system, lighting energy savings ranging from 17.7% to 92.0% could be achieved in the seven cities in Brazil and savings ranging from 10.8% to 44.0% could be achieved in the UK [14].
Menzies & Wherrett	The sustainability and comfort issues of several multi-glazing windows.	A large scale case study involving four buildings was held. The energy use in the buildings was recorded. A survey was conducted to determine the comfort situation.	The daylighting effects of window devices studied can reduce energy use in buildings while make the environment more comfortable. However, if comfort issue was considered first, the energy saving effect will be weakened [15].
Sullivan et al.	To develop a methodology to calculate the HVAC and lighting energy saving from application of daylighting.device	Large number of DOE-2 based simulation was undertaken to form a data base, summary of principles is then conducted from the data base.	A generally good agreement between prediction result from the method developed and case study can be achieved [17].

Recently, with the development of building energy simulation software, researchers were able to make comparisons and summarize principles from large number of cases. Many literatures focus on the structure and optical parameters of window glazing, aiming at exploring their effects on the lighting energy consumption. The ideal window size, direction and types to minimize energy consumption of buildings were studied by Mehlika et al. [16]. Through large number of case simulations, the effect of indoor temperature setting point on the daylighting performance of windows was studied by Kontoleon & Bikas [18], and they claimed that the glazed opening percentages had a huge effect on thermal performance of the buildings. Al-Homound also simulated the daylighting performance under different climate situation and made interesting analysis with other experimental studies [19]. Moreover, Johnson et al. simulated the economically optimum window area and orientations through software simulation [20]. With the support of detailed data, researchers could evaluate the performance of advanced shading or window materials [21].

Lighting and air-conditioning energy uses are the top two components of total building energy consumption. In this paper, a simulation study was conducted to study the comprehensive daylighting and thermal performance of energy-efficient window designs in cooling-dominant climates. Several popular design patterns, namely double-layer glazing, low-e glazing, interior blind and overhang were selected. The main object of the study is to evaluate the cost-effectiveness of these popular design patterns and clearly indicate the impacts of orientation as well as latitudes, so that detailed guidelines could be achieved for practical building design in cooling-dominant climates.

Methodology

Two popular building simulation programs, namely EnergyPlus and Daysim were used in combination in this research. EnergyPlus is a building energy simulation program, which is based on state-space techniques, to calculate the space load required to maintain a set condition in a building installed with a variety of specified HVAC systems. Many previous studies have proved its accuracy and adaptability [22, 23, 24]. Daysim is a dynamic RADIANCE-based daylighting simulation program that calculates the annual daylight amount received within buildings. Daysim allows users to calculate the annual electric lighting energy consumption under certain illumination level set-point. Daysim could be directly coupled with thermal simulation program such as EnergyPlus [25, 26].

A 20-floor high-rise office building model was defined for the simulation study. The office building is a square building with a north-south orientation. The floor area is 100m ×100m. The height of floor is 3.2m. The window-wall ratio of each vertical façade is 0.35. There is no window glazing on roof area. The detailed inside partition of a typical floor is presented in Figure 1.

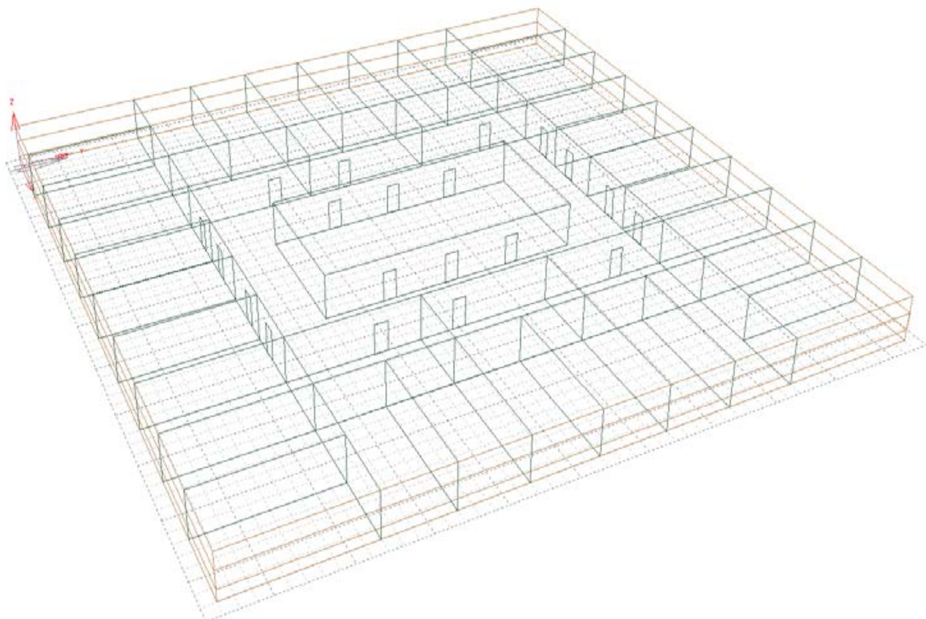


Figure 1 Partition of a typical floor of the building

Four cities with different climates were selected. The four cities from south to north are Singapore, Hong Kong, Miami and Houston. All the four cities are located in Northern Hemisphere. Their latitudes are 1°18´, 22°15´, 25°47´ and 29°45´. Since over 75% of the world populations live within 20°~60° north latitude, the selection of these four cities is considered representative. Within these four cities, solar elevation angle at the same time decrease from south to north. All the four cities are located within cooling-dominant climates.

1. Simulation set up for thermal performance

The details of building construction, including structure and materials of wall, roof, ceiling, floor and window were defined strictly according to local standards of building design [27, 28, 29]. The detailed structure and parameters of wall and roof are shown in Table 1. The peak occupant density was 13 m^2/person. The peak lighting power density was 15W/m^2. The peak equipment power density was 10W/m^2. The minimum fresh air supply was 8

L/s/person. The cooling load caused by infiltration plays an important part in the building cooling load. In the simulation study, a consistent 1m^3/m^{2}h air infiltration was applied, so that the simulation result could be as realistic as possible. The operation schedules of occupant, lighting and equipment are presented in Figure 2 (In air-conditioning schedule, "1" on y-axis stands for "ON" status for air-conditioning system while "0" stands for "OFF" status). During air-conditioning hours, the indoor air temperature was set at 25 ℃. The simulation time step was 10 minutes. The simulation period was 1 year.

Table 1 Detailed data of building materials

A. Wall in Hong Kong and Singapore

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. Roof in Hong Kong and Singapore

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

C. Wall in Houston and Miami

material	Thickness(m)	Conductivity(W/mK)	Density(kg/m^3)	Specific heat(J/kgK)
1IN stucco	0.0253	0.6918	1856	837
8IN concrete HW	0.2032	1.311	2240	837
½ IN gypsum	0.0127	0.16	785	830

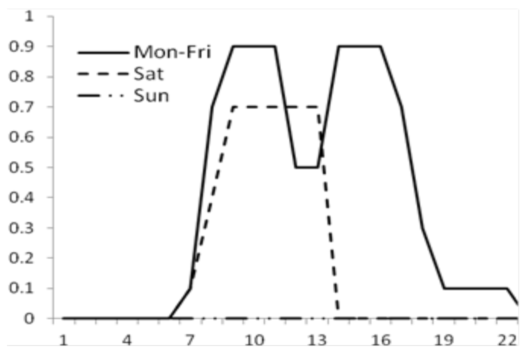
D. Roof in Houston and Miami

material	Thickness(m)	Conductivity(W/mK)	Density(kg/m^3)	Specific heat(J/kgK)
Roof membrane	0.0095	0.16	1121	1460
IEAD NonRes roof	0.0125	0.049	265	837
Metal decking	0.0015	45	7680	418

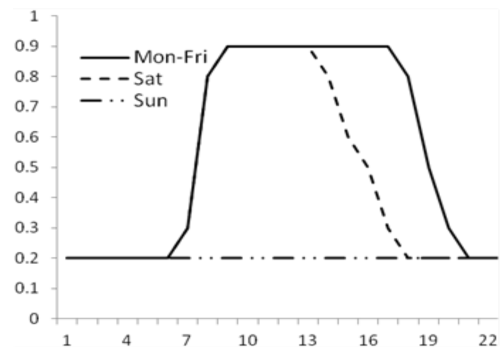
E. Optical features of glass layer applied in simulation

Properties	data

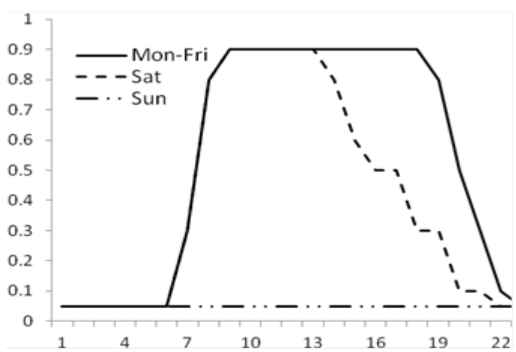
Solar transmittance at normal incidence	0.708
Front side solar reflectance at normal incidence	0.075
Back side solar reflectance at normal incidence	0.075
Visible transmittance at normal incidence	0.753
Front side visible reflectance at normal incidence	0.075
Back side visible reflectance at normal incidence	0.075
Infrared transmittance at normal incidence	0
Front side infrared emissivity at normal incidence	0.84
Back side infrared emissivity at normal incidence	0.84



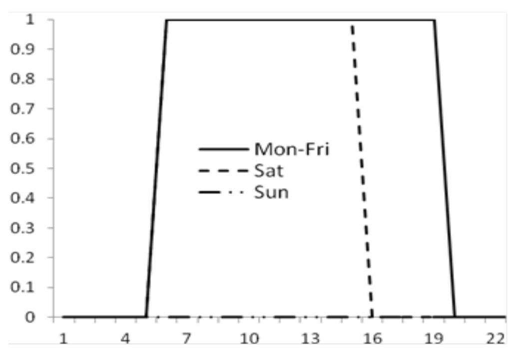
1. Occupant



2. Equipment



3. Lighting



4. Air-conditioning

Figure 2 Schedules setting for occupant, lighting, equipment and fresh air supply

2. Simulation set up for daylighting performance

There are two major factors which directly affect the quality of visual environment: illumination level and illumination distribution. If the illumination level is too low, artificial lighting system will be necessary to maintain a visual comfortable environment. If a significant ratio of luminance appears within a small area, a glare appears, occupants will also prefer to artificial lighting to maintain a satisfactory visual environment. During the daylighting simulation study, both factors should be considered.

During the daylighting simulation, the peak lighting power density was 15W/m^2. The indoor illumination level set point was 500 lux. The lighting control system was set to be “Manual on/off switch near the door” which is a popular lighting control type in commercial buildings. The illumination measuring point matrix was distributed uniformly into each office. The height of illumination measuring points was 0.8 m, which is a typical height of working desk. The maximum allowable Discomfort Glare Index was 22 [30].

Two different occupant behavior models were applied. For the first occupant behavior model, occupants were considered to have no daylighting awareness. They would simply turn on the light above their seats once they arrive at the office, and switch it off while they leave. Under this condition, there was no dimming control of the artificial lighting. The artificial lighting system was set to be strictly operated according to the schedules in Figure 2.The simulation based on the first occupant behavior model is serving as the Base Case. While in the Contrast Case, the occupants were supposed to consider daylighting as priority. While they arrive at the office, the artificial lighting system would be switched off by default, and daylighting is first considered. Only when the illumination level is lower than 500 lux or glare appears, artificial lighting system will be turned on.

In order to analysis the impact of orientation on the daylighting performance of energy-efficient window designs, offices with different orientations were divided into different groups.

Results and discussions

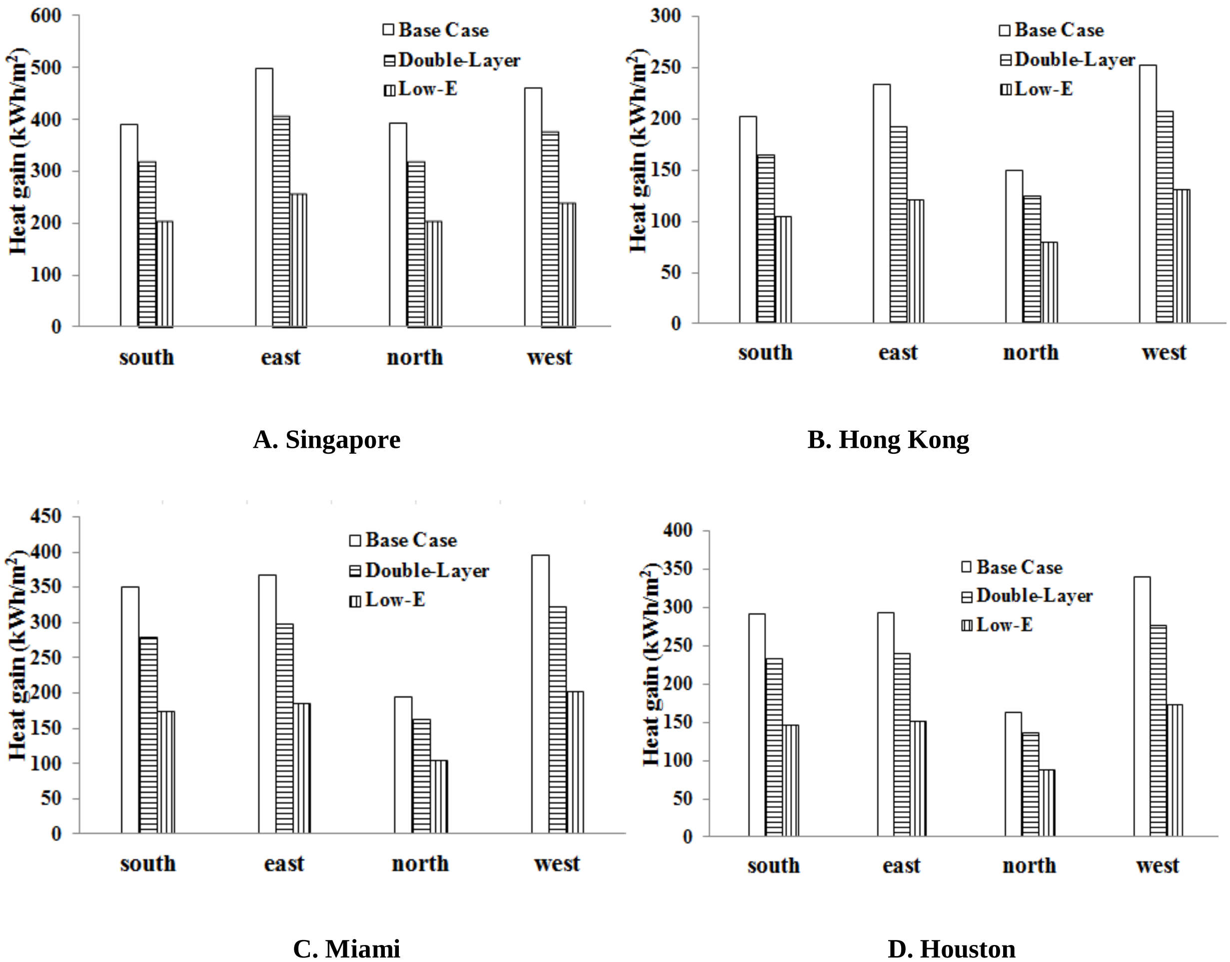
1. Simulation result of the thermal performance of different energy-efficient window designs

1.1 Glazing materials

Double-layer glazing and low-e glazing can be considered as different kinds of glazing materials, thus their performances are discussed in one section in the study. The double-layer glazing applied here was two layers of clear glass described in Table 1 with a 6mm air layer in between. The low-e glazing applied here was double-layer glazing with a low-e coating applied on the inner surface of the outer glazing layer. The optical features of the low-e glazing layer are listed in Table 2. Figure 3 presents the space cooling load caused by window heat gain in different cases. It should be noted that in the following discussion heat gain result is converted into heat gain per unit area of window surface.

Table 2 Optical features of low-e glazing layer applied in simulation

Properties	data
Solar transmittance at normal incidence	0.4
Front side solar reflectance at normal incidence	0.281
Back side solar reflectance at normal incidence	0.403
Visible transmittance at normal incidence	0.742
Front side visible reflectance at normal incidence	0.064
Back side visible reflectance at normal incidence	0.052
Infrared transmittance at normal incidence	0
Front side infrared emissivity at normal incidence	0.84
Back side infrared emissivity at normal incidence	0.05



A. Singapore B. Hong Kong

C. Miami D. Houston

Figure 3 Thermal performances of double-layer glazing and low-e glazing

The application of double-layer glazing in cooling-dominant area can reduce window heat gain by around 15% ~20%. Compared to single-layer glazing, double-layer glass has an extra glass layer which can help block out part of solar radiation. When radiation projected on the second glazing surface, part of it travels directly through, part of it is reflected back to the backside of the first glazing layer, and the rest of it is absorbed by the glazing material. Part of the absorbed radiation will be radiated into the room by long-wavelength radiation. The reflected part of radiation will again be absorbed and reflected by the first glazing layer, and then repeats previous process. Therefore while introducing in the second glazing layer what really matters is the “blocking” effect of glass material. With respect to low-e glazing, the performance is even better. While low-e glazing presented in Table 2 is applied, window heat gain was cut by almost 50%.

1.2 Interior blind

Compared to external shading devices like overhang, one key advantage of blind is its adjustability. The occupants can adjust the tilt angle of louvers according to outdoor weather condition. Obviously the performance of blind depends largely on the tilt angle of blind louver. Figure 4 below presents the definition of tilt angle used in the simulation. As the tilt angle gets smaller, less solar radiation is allowed to get into the building. Window heat gain is reduced, while daylighting effect is also weakened. According to previous study, occupants do not adjust interior blind very often. They tend to set the blinds in certain positions based on long-term perceptions of sun light and sun heat, and then just leave them there [31, 32]. In this study, the impact of occupant behavior was investigated. Performances of interior blind with three different tilt angles were simulated. The simulation results of the thermal performance are presented in Figure 5.

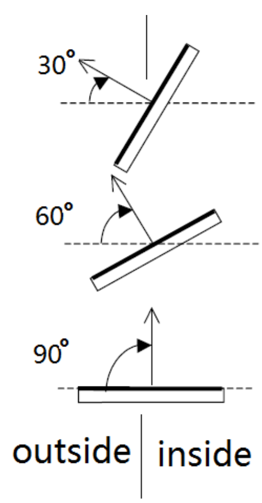
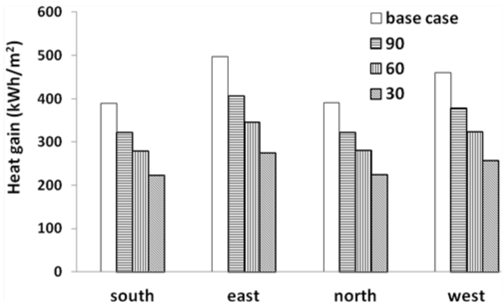
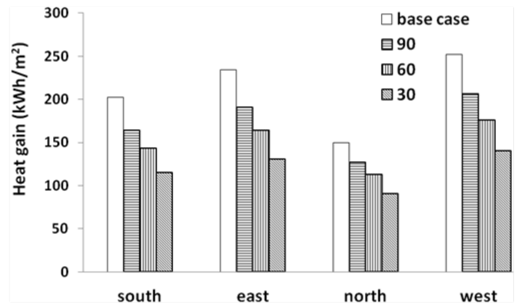


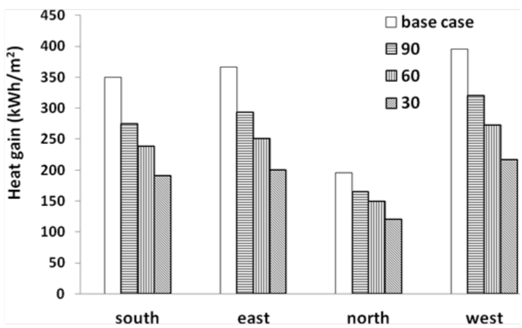
Figure 4 Definition of blind tilt angle



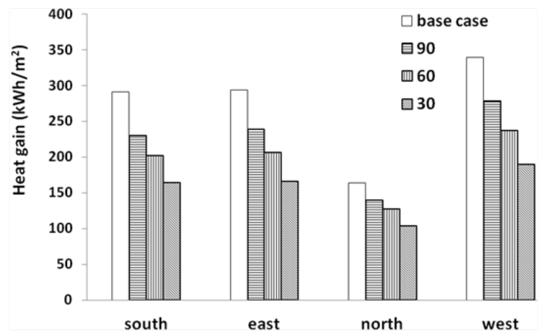
A. Singapore



B. Hong Kong



C. Miami



D. Houston

Figure 5 Effect of tilt angle on blind performance

In Singapore, heat gain on each façade does not vary a lot. The interior blind on the east and west facades can cause about 20% more heat gain reduction of the building than those on the south and north orientations. The blind on the south façade reduces the least heat gain compared with those on the other facades. In Hong Kong, the blind on the south façade contributes almost the same as those on the east and west façades. The north facing blind reduces only less than half of the heat gain compared with devices facing the other orientations. With respect to Houston and Miami, performance of the blind on the north façade drops to only 1/3 of blind facing the other orientations.

The influence of louver tilt angle on the blind is quite significant. In most cases, setting the slat angle at 90° can only reduce the window heat gain by about 15% to 20%, while setting the slat angle at 30° a reduction of around 40% to 50% is achieved. It can be concluded that as the slat angle decreases, the thermal performance of the blind will be even better.

Louvers' reflectivity is also an important parameter that affects the blind's performance. Figure 6 presents the thermal performance of interior blinds with different reflectivity in Hong Kong.

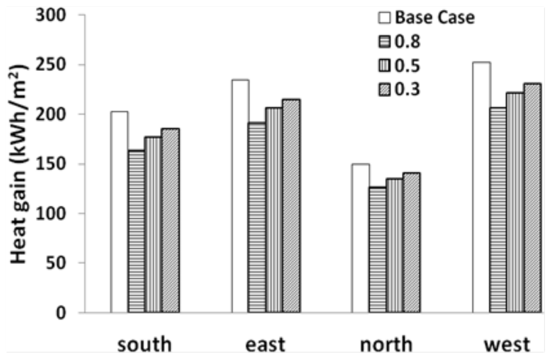
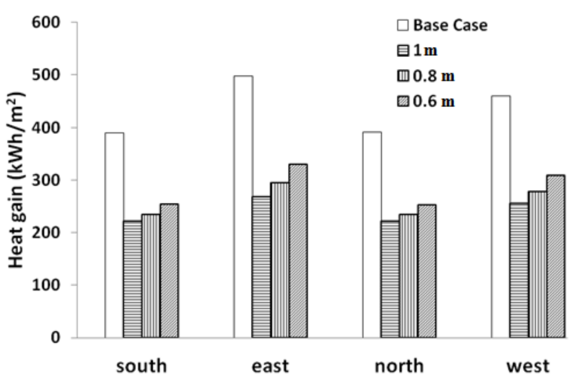


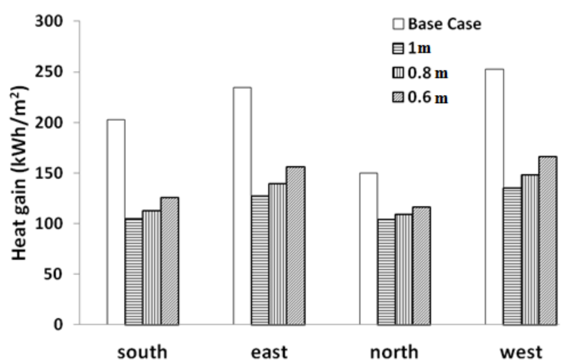
Figure 6 Thermal performances of interior blind with different reflectivity in Hong Kong

1.3 Overhang

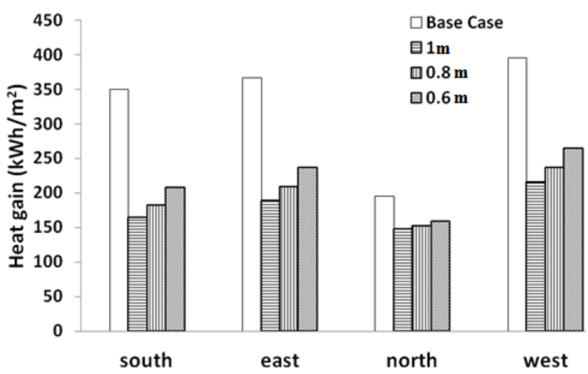
Overhang may be the most traditional and popular shading design in the world. The depth of overhang is a key factor that affects the performance. Figure 7 presents the thermal performance of overhangs with depth from 0.6m to 1m. It should be noted that the height of window in this study was 1.2m.

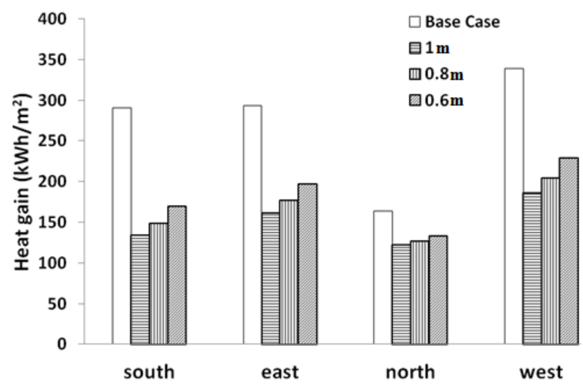


A. Singapore



B. Hong Kong





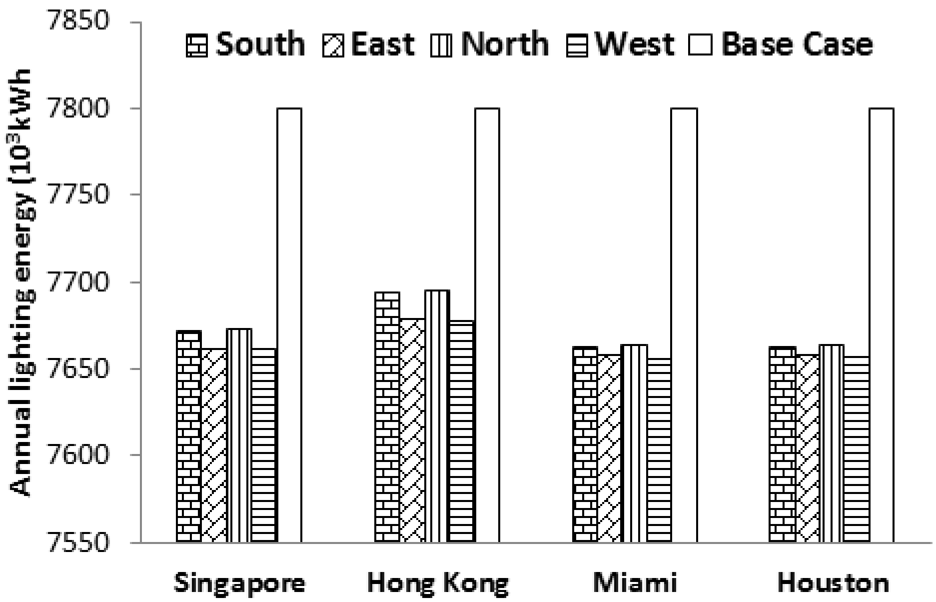
C. Miami **D. Houston**

Figure 7 Thermal performance of overhang with different depth

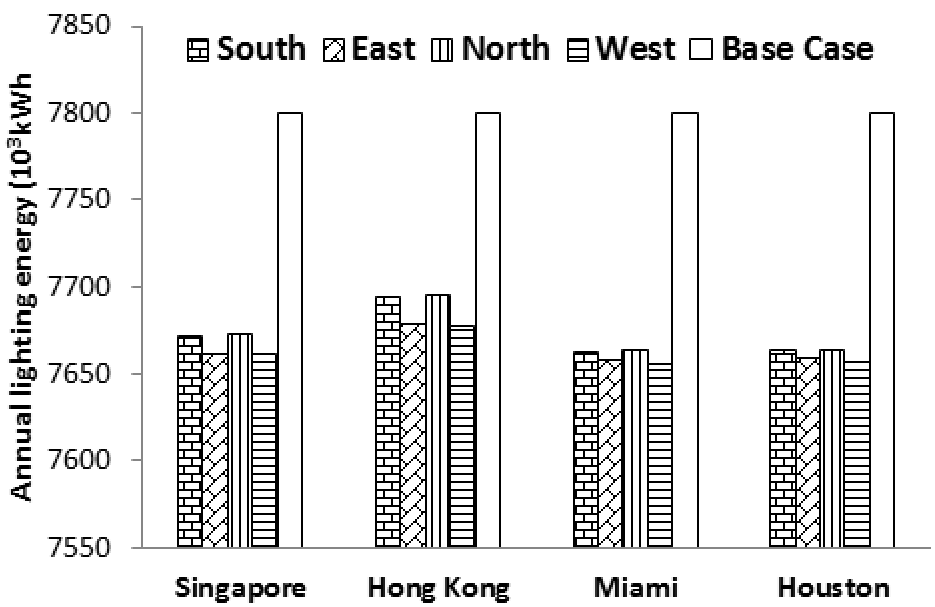
When the overhang depth is more than half of the window's height, the impact of overhang depth is not very significant. The impact of depth is higher on overhangs facing the east and west. In practical projects, overhangs facing east and west can be a little longer. With respect to the north façade, a short overhang or interior shading could be considered.

2. Simulation result of the daylighting performance of different energy-efficient window designs

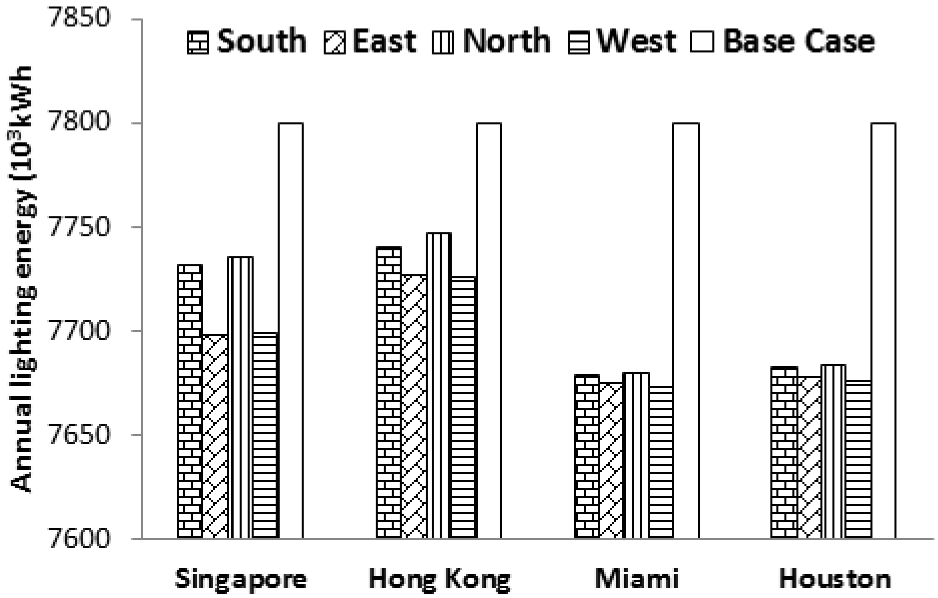
Figure 8 gives the annual artificial lighting electricity reduction from application of daylighting strategy. Case A, Case B, Case C and Case D are lighting energy consumption in the Contrast Case. Case A stands for the result with the application of double-layer glazing. Case B stands for the result with the application of low-e glazing. Case C stands for the result with the application of interior blind (the blind tilt angle is 90°). Case D stands for the result with the application of overhang (the depth of the overhang is 1m).



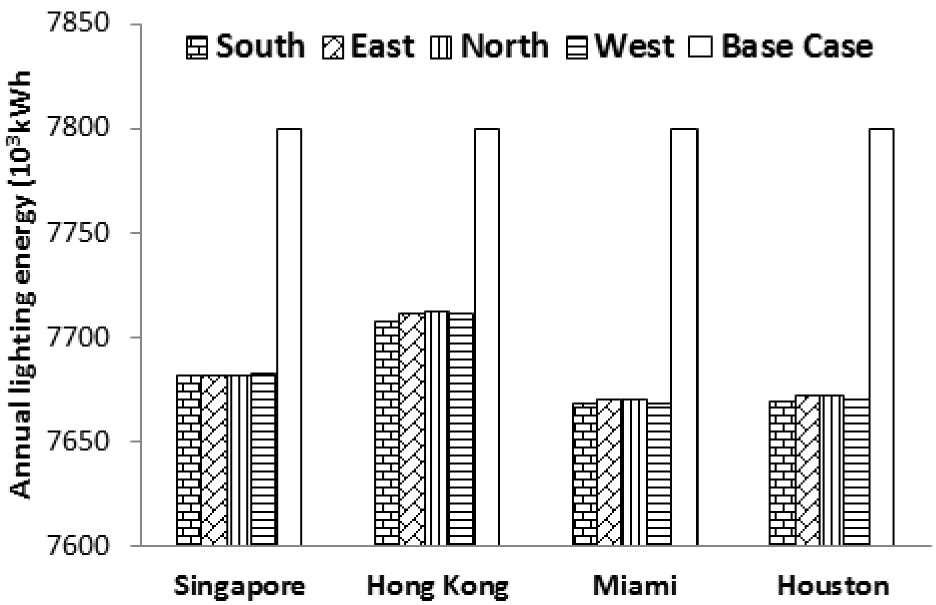
1. Case A



2. Case B



3. Case C



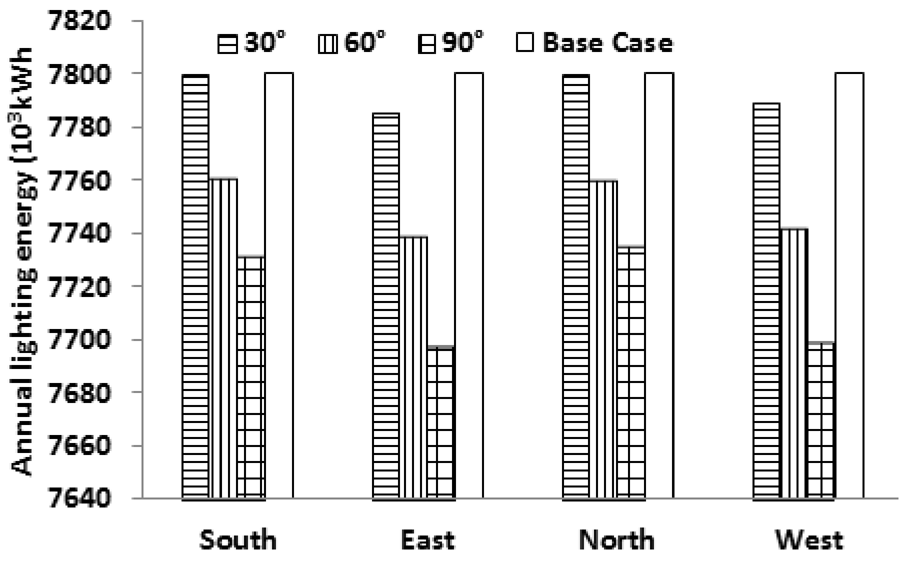
4. Case D

Figure 8 Annual lighting energy consumption in different cases

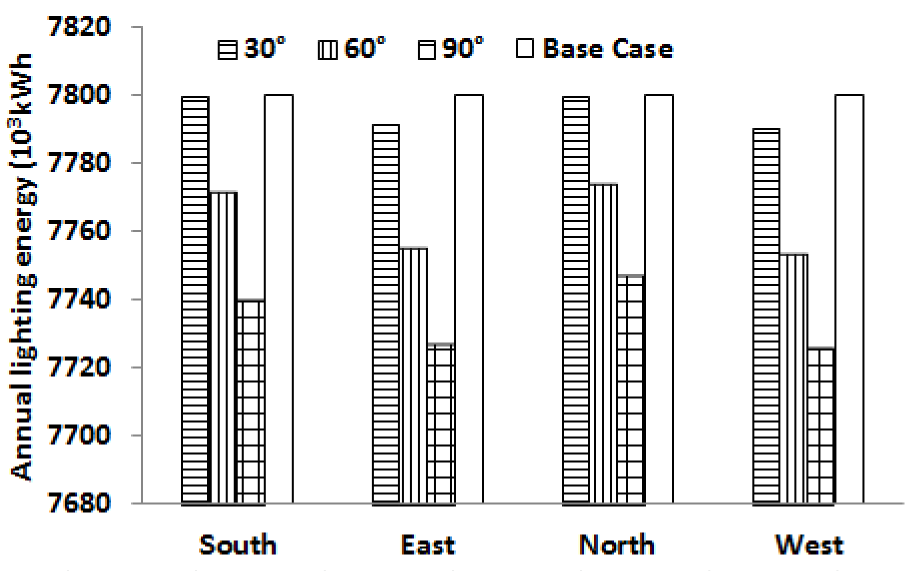
Before the discussion, it should be noticed that in the Base Case, the annual lighting energy consumption is 7.8×10^6 kWh, while in all the Contrast Cases, the annual lighting energy saving are around 1.5×10^5 kWh. The proportion is small. The reason lies in the shape coefficient of the model building. The shape coefficient is the ratio of the area of building's external surface to the building's volume. The shape coefficient characterizes the impact of external environment to the building's indoor environment. A small shape coefficient stands for a small impact of external environment to the building indoor environment [33]. In this study, the model building was a simple square building with a large interior zone. The shape coefficient can be calculated to be 0.056, which means the impact of outdoor environment on the building energy consumption is rather small. In this case, the lighting energy saving from daylighting is also relatively small. From the simulation result of the case it can be concluded that in buildings with small shape coefficient, the design of window should consider thermal performance as priority. In buildings with larger shape coefficient, daylighting performance will be better. However, it does not mean daylighting is not effective in office buildings. Actually, though the proportion is small, the lighting energy saved from daylighting is still rather considerable. Besides, the difference among different cases also follows certain pattern that worth discussion.

From the simulation result it is clear that in almost all cases, daylighting performances on the east and west orientations are better than those on the south and north orientations. In low latitude area like Singapore, the difference is much larger. In double-layer glazing cases, the difference between daylighting performance of the east, west orientations and the south, north orientations is within 10%. In interior blind cases, the difference is almost 50% in Singapore and 25% in Hong Kong.

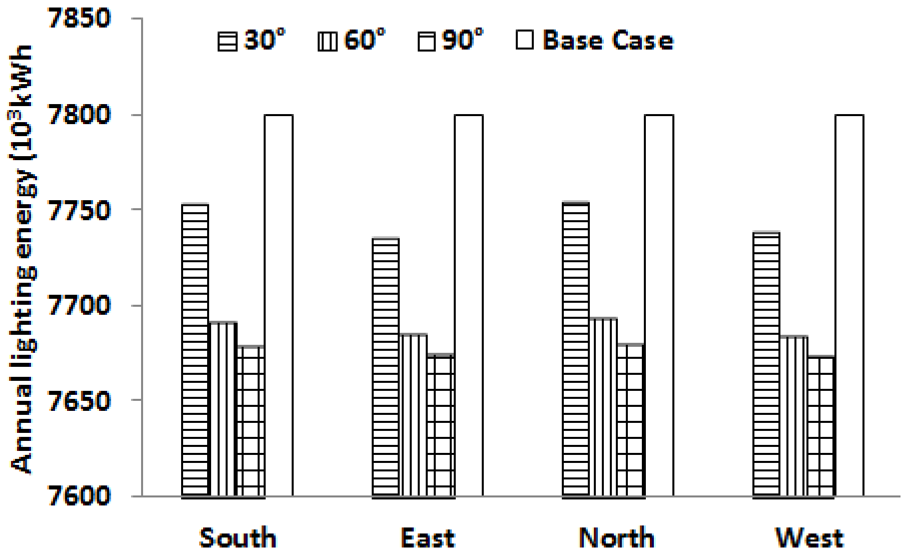
Compared with double-layer glazing and low-e glazing cases, daylighting performances of interior blind in Singapore and Hong Kong are significantly worse. While in Miami and Houston, the gap between daylighting performances of shading device and energy-efficient glazing is much smaller. In cooling-dominant area with relatively low latitude, application of interior blind will significantly affect the daylighting performance, while in area with high latitude the influence is not that much. The daylighting performance of overhang equipped window is almost the same as the daylighting performance of double-layer glazing and low-e glazing. Daylighting performance of interior blind is the worst within all window design measures studied.



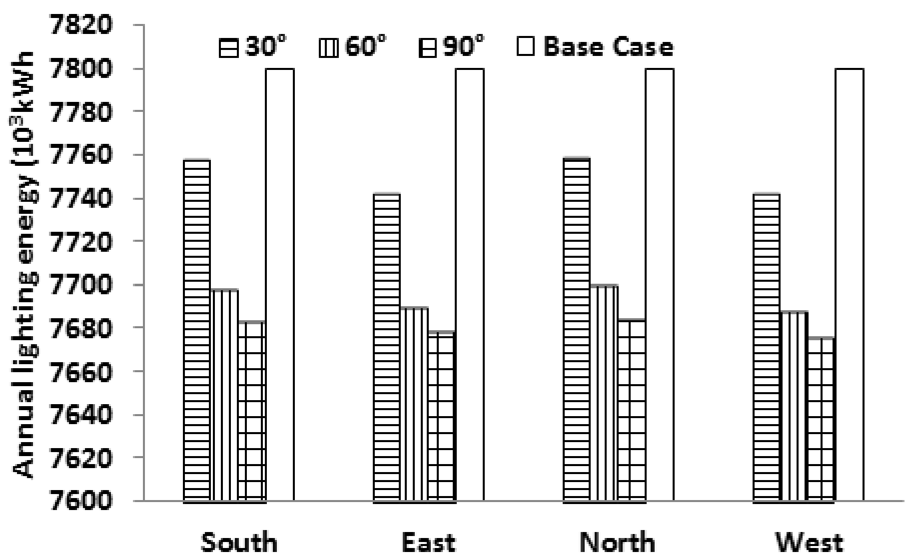
1. Singapore



2. Hong Kong



3. Miami



4. Houston

Figure 9 Annual lighting energy saving from daylighting with different blind tilt angle

The daylighting performance of interior blind is also significantly affected by the louver tilt angle. As shown in Figure 9, in Singapore and Hong Kong, the daylighting performance drops rapidly with the tilt angle. While the tilt angle decreases to 30°, Daylighting profits on the south and north orientations completely disappear. Daylighting profits on the east and west orientations also drop to a very low level. In Miami and Houston, though there is a drop on daylighting performance when the tilt angle gets smaller, daylighting effects on all orientations are still retained.

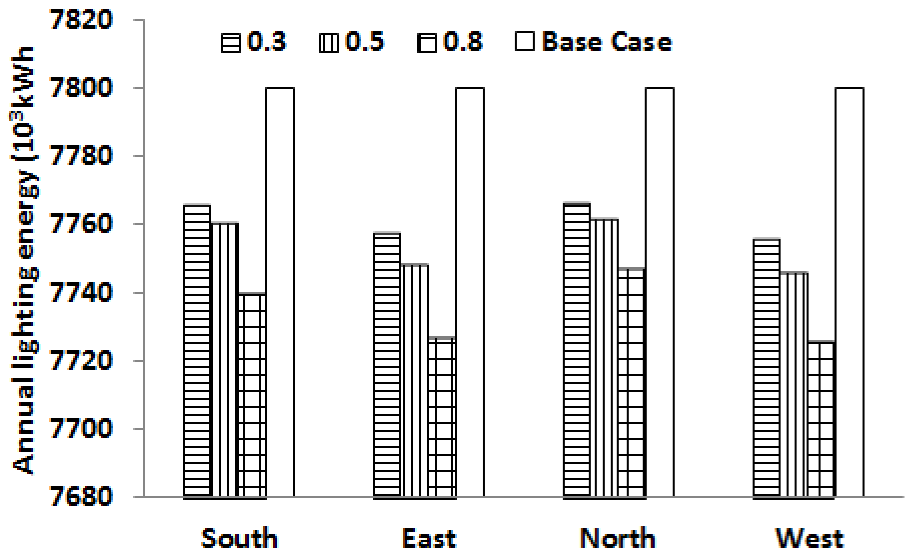
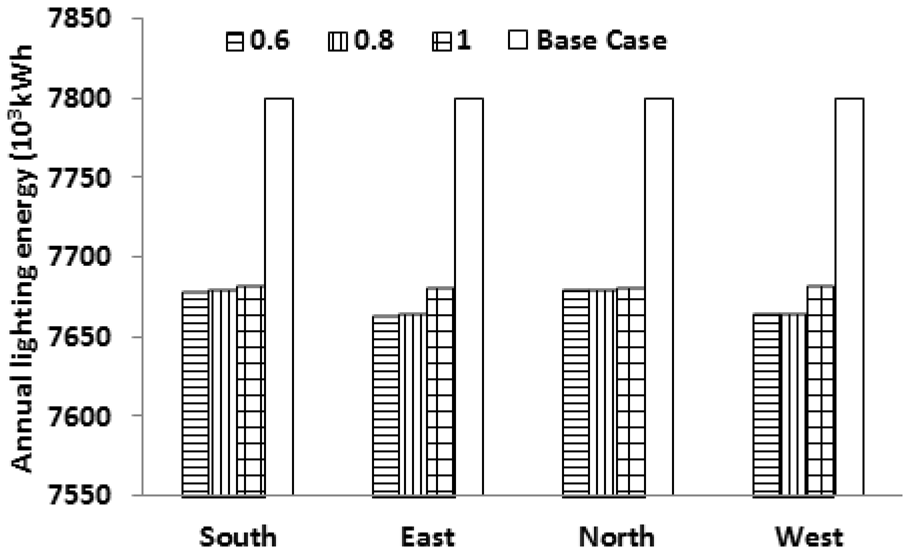
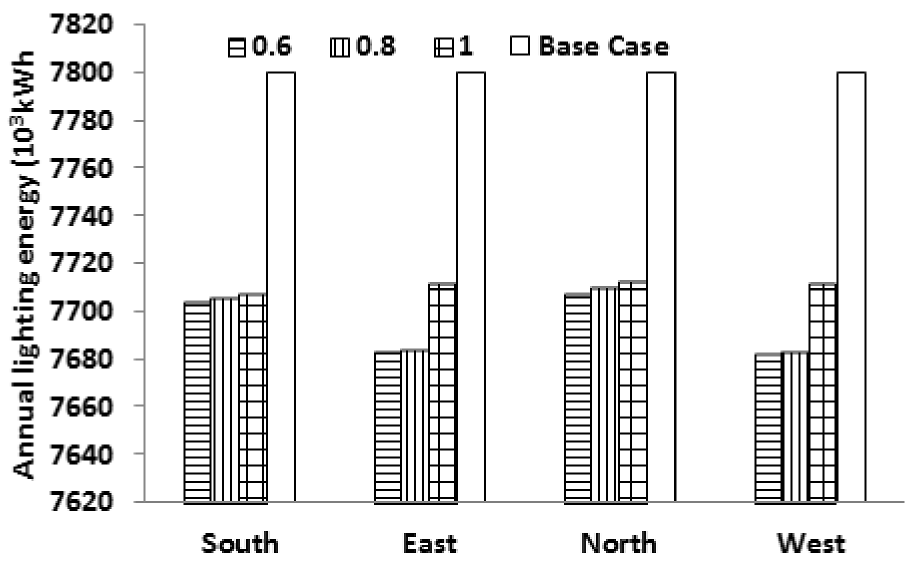


Figure 10 Annual lighting energy saving from daylighting with different blind louver reflectivity in Hong Kong

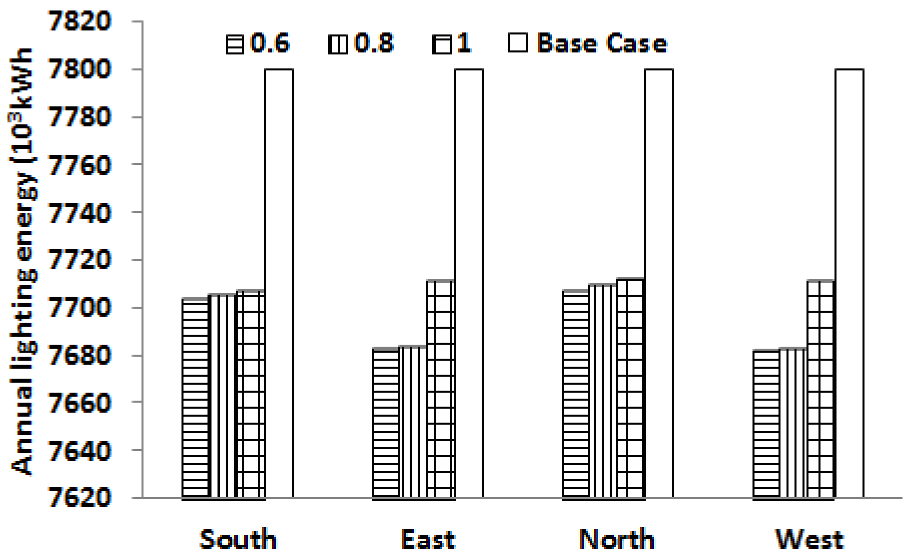
The reflectivity of blind louver is also an important factor that affects the performance of blind. Figure 10 gives the simulation result for the annual lighting energy saving with different blind louver reflectivity. Due to length limitation, only result of Hong Kong is presented here. From above data an interesting conclusion can be achieved. With the decreasing of reflectivity, the thermal performance of blind also drops. When the reflectivity decreases to 0.3, the performance of blind drops to less than half. Similar results can be achieved from results of the other three cities, of which the results are not presented due to length limitation.



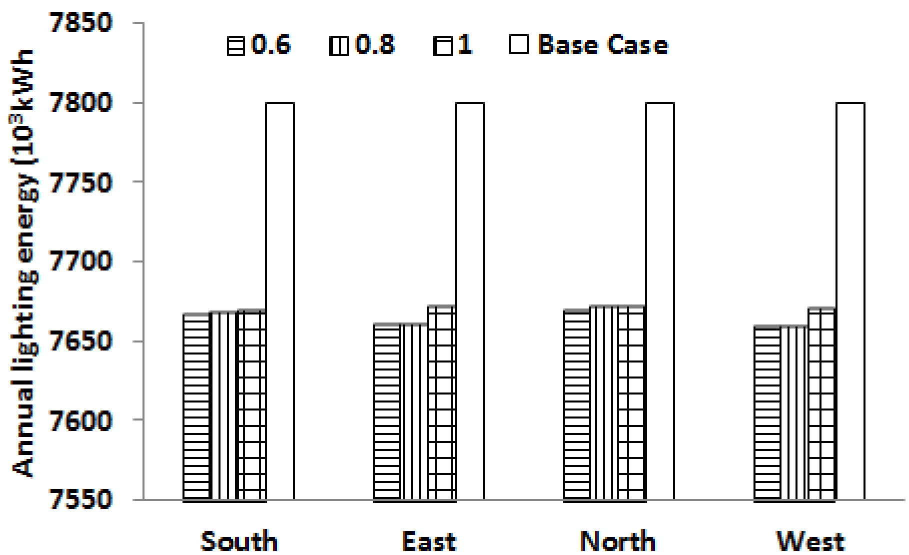
1. Singapore



2. Hong Kong



3. Miami



4. Houston

Figure 11 Annual lighting energy saving from daylighting with different overhang depth

Figure 11 presents the annual lighting energy saving from daylighting with different overhang depth. As the depth increases, daylighting performance of the overhang becomes worse. The decrease in daylighting performance is significant on the east and west orientations. As the latitude rises, the affection of depth on daylighting performance on east and west orientations becomes smaller. In Hong Kong, when the overhang depth changes from 0.6m to 1m, daylighting performances on the east and west orientations even drop to less than 80%. While in Miami, when the overhang depth changes from 0.6m to 1m, daylighting performances on the east and west orientations drop to over 90%.

3. Comprehensive evaluation considering both thermal and daylighting performances

Window is an important and indispensable element in modern architecture. Window can supply the occupants with an access to the day lighting and pleasant outside view, which is considered to be a valuable feature in high-rise cities. Window is also, however, a major route of the large amount of unwanted solar heat gain. The two conflicting considerations bring forward a challenge in the window design area.

In cooling dominant area, applying energy efficient window designs on building envelope can largely reduce heat gain through window area, which is a major component of the building air-conditioning system load. Since almost all of the heat gain through window is radiation heat gain, the thermal resistance of glazing material cannot affect the window's thermal performance significantly. Application of double-layer glazing can reduce the window heat gain by about 15% to 20%. Application of low-e glazing can achieve an even higher reduction. When low-e glazing described in Table 2 is applied, the window heat gain reduction can be as much as 50%. As shown in Figure 8, the daylighting performance of the low-e glazing stays almost the same as that of the double-layer glazing. Considering that low-e glazing has a better thermal performance than double-layer glazing, low-e glazing is a better choice for energy-efficient design and retrofitting than double-layer glazing in cooling-dominant climates.

According to the simulation result, the interior blind installation can help reduce window heat gain by around 20% blind while louver's tilt angle is 90°, and the thermal performance of the blind decreases as the reflectivity decreases. As presented in Figure 10, daylighting performance of the interior blind also decreases with the louver's reflectivity. The impact of occupant's behaviour on the blind's performance also gets smaller as the reflectivity rises. Thus it is clear that the louver's reflectivity is the key factor that affects the blind's comprehensive performance. The higher the reflectivity is, the better the blind performs.

As shown in Figure 7, a reduction of around 40% in window heat gain can be expected with the application of overhang. As the depth gets larger, the thermal performance gets better. However, the daylighting performance drops as the depth increases. While the overhang's depth changes from 0.6 m to 1 m, its thermal performance is improved by about 20%, while its daylighting performance drops around 8%-10% in most cases. Depth is the key factor that affects the comprehensive performance of overhang. There exist an ideal depth so that the overhang could block out large amount of solar radiation while still retain an acceptable amount of daylight.

It is clear from the simulation that the thermal performance of overhang is better than interior blind while louver's tilt angle is 90°. Although reducing the tilt angle of blind would improve the thermal performance of the blind, gaps still exist in most cases. As shown in Figure 8, the daylighting performance of overhang is also better than that of interior blind. As the tilt angle decreases, the blind's daylighting performance gets weaker. Thus in the respect of comprehensive performance, overhang is a better shading choice than interior blind in cooling-dominant climates.

As discussed above, in low-e glazing case, the window heat gain reduction can be as much as 50%, while a reduction of around 35% to 40% in window heat gain can be expected with the application of overhang. Also as shown in Figure 8, the daylighting performance of overhang equipped window is almost the same as the daylighting performance of double-layer glazing and low-e glazing. Overall speaking, the comprehensive performance of the low-e glazing is better than that of the overhang. In cooling-dominant climates, low-e glazing is the best energy-efficient window design considering both thermal and daylighting performances.

While the tilt angle of louver is set at 90°, the performances of blind and double-layer glazing are at the same level. But the flexibility of blind makes it able to deal with shading and daylighting under different weather condition, while double-layer glazing may easily suffer from glare or overheating. From this perspective, double-layer glazing may be the last choice for window design in cooling-dominant climates.

Orientation is an important factor that affects the performance of energy-efficient window designs. In order to better quantify the cost-effectiveness of energy-efficient window designs, heat gain reduction of three different designs (low-e glazing described in Table 2, interior blind with a reflectivity of 0.8 and a louver tilt angle of 90°, overhang with a depth of 1m) on office building façade facing different orientations in four cities and their proportions in the total envelope surface heat gain are compared in Table 3 below. Two variables, namely δ and γ are defined to make the discussion easier:

$$\delta = \frac{M}{W} \times 100\% \qquad (1)$$

$$\gamma = \frac{M}{G} \times 100\% \qquad (2)$$

W (kWh) represents the annual heat gain through window area. G (kWh) stands for the annual heat gain through building façade. M (kWh) is the annual heat gain reduction from different window designs.

Table 3 Thermal performance of three different window designs on different orientations

A. Singapore

Orientation	Low-e glazing			Blind			Overhang		
	M(kWh)	δ	γ	M(kWh)	δ	γ	M(kWh)	δ	γ
South	484,586	11.6%	10.1%	162,845	3.9%	3.4%	400,516	9.6%	8.3%
East	615,952	14.7%	12.7%	218,155	5.2%	4.5%	549,131	13.1%	11.3%
North	485,540	11.8%	10.0%	165,252	4%	3.4%	405,652	9.7%	8.4%
West	571,504	13.6%	11.6%	196,918	4.7%	4%	491,024	11.8%	10.1%
Total saving	2,157,582	51.7%	44.4%	743,170	17.8%	15.3%	1,846,324	44.2%	38%

B. Hong Kong

Orientation	Low-e glazing			Blind			Overhang		
	M(kWh)	δ	γ	M(kWh)	δ	γ	M(kWh)	δ	γ
South	248,462	12.3%	10.1%	92,694	4.6%	3.8%	234,806	11.7%	9.7%
East	290,100	14.3%	12.1%	103,482	5.1%	4.3%	256,976	12.8%	10.6%
North	189,964	9.4%	8.0%	54,556	2.7%	2.3%	108,708	5.4%	4.5%
West	311,273	15.5%	13.0%	110,516	5.5%	4.6%	281,881	14%	11.6%
Total saving	1,039,795	51.5%	42.9%	361,248	17.9%	14.9%	882,373	43.8%	36.5%

C. Miami

Orientation	Low-e glazing			Blind			Overhang		
	M(kWh)	δ	γ	M(kWh)	δ	γ	M(kWh)	δ	γ
South	416,319	13.2%	12.1%	179,526	5.7%	5.2%	444,455	14.2%	12.9%
East	443,908	14.1%	12.9%	175,699	5.6%	5.1%	426,027	13.6%	12.4%
North	247,777	7.6%	7.2%	72,122	2.2%	2.1%	115,456	3.7%	3.3%
West	481,484	15.3%	13.9%	179,792	5.7%	5.2%	431,147	13.7%	12.6%
Total saving	1,589,487	50.5%	46.3%	607,140	19.3%	17.7%	1,417,088	45.2%	41.3%

D. Houston

Orientation	Low-e glazing			Blind			Overhang		
	M(kWh)	δ	γ	M(kWh)	δ	γ	M(kWh)	δ	γ
South	349,151	13.4%	11.9%	146,437	5.6%	5%	375,747	14.4%	12.8%
East	360,146	13.8%	12.4%	130,492	5%	4.5%	316,064	12.1%	10.8%
North	207,162	8.0%	6.9%	56,978	2.2%	1.9%	97,426	3.7%	3.3%
West	414,414	15.8%	14.1%	147,206	5.6%	5%	366,970	14%	12.5%
Total saving	1,330,872	50.9%	45.4%	481,113	18.4%	16.4%	1,156,208	44.3%	39.5%

From Table 3, it is clear that the thermal and daylighting performances of all the three window designs are better on the east and west orientations. On the north orientation, both thermal and daylighting performances are the worst.

Geography location could also affect the performance of different window designs. Although there exist difference in both thermal and daylighting performance on different orientations, as the latitude rises, the difference becomes smaller. The impact of depth on overhang also decreases as the latitude rises.

Conclusion

In this paper, the thermal and daylighting performance of several popular energy-efficient design measures on office building window was simulated and discussed. The factors that may affect the performance of different measures were investigated. A comprehensive evaluation is also presented to assess the overall energy performance of different window designs.

Window is a major source of solar heat gain for commercial buildings. At the same time window is also an important architecture element which supplies the occupants with daylight and outdoor viewing. Large window area can ensure a considerable saving of lighting energy via daylighting, at the same time large window area also lets in large amount of unwanted solar radiation. The combination between daylighting and solar shading requires extra attentions.

In cooling-dominant climates, employing several popular energy-efficient designs on window can reduce a large amount of solar heat gain while still retain a satisfactory level of daylighting. Among the window designs discussed in this paper, the low-e glazing is the best choice considering both thermal and daylighting performance, while double-layer glazing performs the worst. The comprehensive performance of overhang is better than that of interior blind. But the adjustability of blind makes it a competitive selection.

Orientation and geography location can make significant affections on the thermal and daylighting performance of window designs. In cooling-dominant climates, all the window designs performs better on the east and west orientations, while the worst performance occurs on the north orientation. In areas with low latitudes, the difference among orientations is quite obvious. As the latitude rises, the difference becomes insignificant.

It is also discovered that the louver's reflectivity is the key factor that affects the blind's comprehensive performance. The higher the reflectivity is, the better the blind performs.

Though low-e glazing can achieve an excellent thermal and daylighting performance, there still exist possible uncomfortable features such as overheating and glare. Searching for advanced glazing materials with better thermal and visual properties will still be the focus of the future.

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