# AUTOMATED SLAT ANGLE CONTROL OF VENETIAN BLIND CONSIDERING ENERGY AND VISUAL COMFORT

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## ABSTRACT

Windows are the only part in buildings that can directly penetrate the solar radiation into the space and thus the shading devices are needed to control the solar penetration. In this study, optimized slat angle control strategies of venetian blinds are suggested. In the development process of the slat angle control strategy, annual cooling, heating, lighting energy and Daylight Glare Index performances are evaluated for each slat angle in the first hand, and then those comprehensive performances are categorized under different window solar radiation regions with the increment of 100 W/m$^2$. After deriving the optimum slat angle showing the lowest total energy for cooling, heating and lighting in each solar radiation region, the slat angle showing the DGI greater than 22 is excluded. As a result, 29.2% of energy saving could be achieved and at the same time the chance of glare was only 0.1%.

## INTRODUCTION

Great amounts of effort have been made to reduce the building energy consumptions these days. Solar radiation control is one of the essential factors to improve the building energy efficiency, especially under the Korean climatic condition having four distinct seasons with a hot and humid summer and a cold winter. Windows are the only part in buildings that can directly penetrate the solar radiation into the space and thus the shading devices are needed to control the solar penetration (Datta 2001) (Oh 2012).

Venetian blinds have up/down control to avoid the glare and at the same time they have great flexibilities to adjust the slat angle under each circumstance. In addition, the direct solar radiation can be fully isolated and the high quality diffuse solar radiation can be introduced into the space through the reflection of solar radiation from each slat (Breitenbach 2001) (Oh 2012).

However, the manual control of blinds by occupants is not an efficient way to reduce the building energy. Occupants do not usually pay attention to the blinds and they are usually closed without any operations by occupants (Paik 2006). Keeping the blind closed can block the solar radiation which should be introduced to reduce the heating load in winter and can increase the artificial lighting energy due to the blockage of the day-lighting. Therefore, the automated control of blinds is necessary to overcome the limitations of manual blind control (OH 2012).

In this study, the optimized automatic control strategies of venetian blinds were developed to efficiently adjust the solar radiation through the window, which can improve both energy efficiency and visual comfort by taking into account cooling, heating and lighting energies as well as the glare phenomena (Oh 2012).

## METHODS

In order to overcome the functional and control limitations of roll blinds commonly used in office buildings, optimized control strategies of slat-type blinds are suggested in this study.

The optimized control strategy was developed based on the total annual building energy consumption and the Day-light Glare Index (DGI) adjacent to windows to be maintained below 22. The control strategies of hourly slat angle and hourly up/down control logic were developed depending on the solar radiation condition (Oh 2011, 2012).

The performance of the developed automatic control strategies of slat-type blinds integrated with the artificial lighting control was quantitatively evaluated by taking into account cooling, heating and lighting energy consumptions and DGI (Oh 2011, 2012).

### Simulation software

A robust building energy simulation program, EnergyPlus version 6.0, was used for the simulations. EnergyPlus is a whole-building energy simulation program developed by DOE (DOE 2010) and is a heat balance based simulation program, which is the current industry standard method for calculating space loads (ASHRAE 2009). Furthermore, it has the capability to perform the detailed energy balance analysis of solar radiation, heat transfer and air movement between window and blind (DOE 2010).

Blind properties for direct radiation are sensitive to the profile angle, which is the angle of incidence in a plane that is perpendicular to the window plane and to the direction of the slats. The blind optical model in EnergyPlus is based on Simmler's model (DOE 2010) (Simmler 1996). In addition, the effect of inter-reflection of the interior illuminance/luminance between interior reflecting surfaces is calculated using a radiosity method derived from Superlite (DOE 2010) (Modest 1982). This method subdivides each reflecting surface in the zone into nodal patches and uses view factors between all nodal patch pairs in an iterative calculation of the total contribution of reflected light within the zone (DOE 2010). For more information on the assumptions, detailed algorithm and validation of EnergyPlus models related to windows, blinds and day-lighting calculations, refer to the document by DOE (2010) (Oh 2012).

**Description of simulated building**

A three-story office building located in Daejeon City, South Korea having a rectangular shape with the window-to-wall ratio (WWR) of 65% was selected for this study. TMY weather data of Daejeon City developed by the Korean Solar Energy Society was used for the simulation. South Zone 2 in the middle floor illustrated in Figure 1 was selected as the simulation model to develop the automatic control strategy of venetian blind (Oh 2011, 2012).

Constructions and the thermal properties of windows and walls comply with the Korean Standard for Energy Saving Design in Buildings (KMLTMA 2010). Double pane windows (6 mm clear glass + 12 mm air + 6 mm clear glass) with the SHGC, visible transmittance and U-value of 0.765, 0.812 and 2.72 $W/m^2K$, respectively were used. Combined properties of double-pane window with the frame have the SHGC, visible transmittance and U-value of 0.666, 0.678 and 2.977 $W/m^2K$, respectively (Oh 2011, 2012).

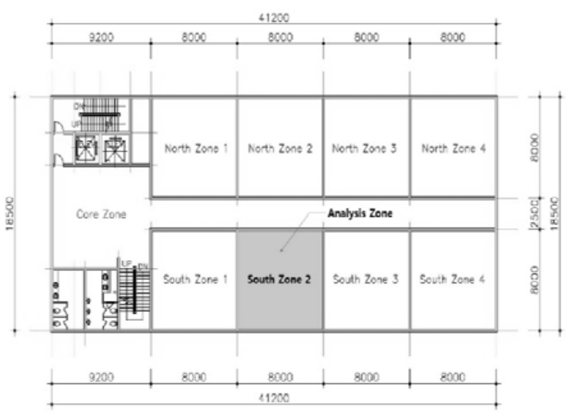


**Figure 1. Plan view of the simulated building (Oh 2011, 2012)**

The physical properties of venetian blind for the simulation analysis is summarized in Table 1 (Oh 2011, 2012).

Table 1. Blind properties

| Field | Unit | Value |
|---|---|---|
| Blind position | - | Inside Blind |
| Slat width | m | 0.048 |
| Slat to slat distance | m | 0.048 |
| Slat thickness | m | 0.002 |
| Blind to glass distance | m | 0.050 |
| Slat solar and visible reflectance | - | 0.500 |
| Slat infrared hemispherical emissivity | - | 0.900 |
| Slat conductivity | W/m·K | 0.900 |
| Slat angle | ° | 45 |

**Indoor set-points, ventilation rate, and HVAC system**

From 6:00 through 19:00 during the weekdays the system controls the internal air temperature to heating and cooling temperature set-points of 22°C and 26°C, respectively. During the night-time the system was switched off without set-back control. The thermal and lighting load profiles were calculated using the EnergyPlus function "ZoneHVAC:IdealLoadsAirSystem" (DOE 2010) without modelling the heating and cooling systems. This object provides the required supply air capacity to each zone at user specified temperature and humidity ratio to calculate the heating and cooling loads (Oh 2012). Infiltration was assumed equal to 0.5 ACH and the ventilation was set to be 1.0 ACH.

**Internal heat gains**

The peak internal load levels are summarized in Table 2 and the hourly variations of the internal loads for the simulated office building follow the schedules shown in Figure 2. HVAC systems operate from 6:00 through 19:00 during the weekdays and from 6:00 through 17:00 on Saturdays (Oh 2012).

Table 2. Internal load level

| Internal load type | Maximum value |
|---|---|
| Overhead lighting, $W/m^2$ | 10.8 |
| Peak occupancy, $m^{2/}$person | 17.0 |
| Equipment $W/m^2$ | 8.6 |

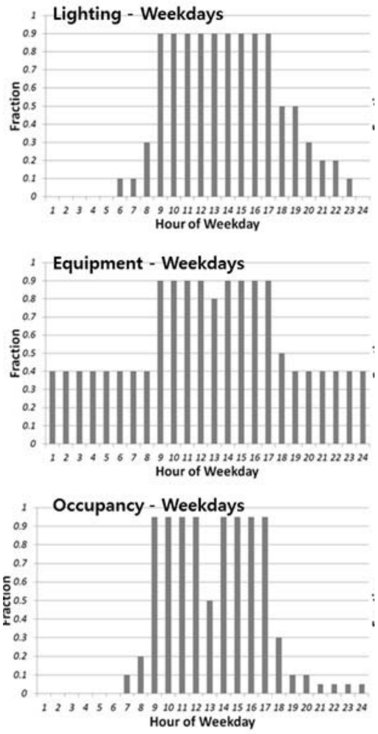


**Figure 2. Lighting, equipment and occupancy schedules (Oh 2012).**

## BLIND CONTROL LOGIC

The automated control strategy of the venetian blind is developed in this study for complete removal of the glare and the energy saving. In the development process of the control strategy, annual cooling, heating, lighting energy and DGI performances are evaluated for each slat angle in the first hand, and then those comprehensive performances are categorized under different window solar radiation regions with the increment of 100 W/m$^2$ (Oh 2011, 2012). After deriving the optimum slat angle showing the lowest total energy of cooling, heating and lighting in each solar radiation region, the slat angle showing the DGI of greater than 22 is excluded. This control strategy of the blind slat angle is finally developed by drawing the trend line after connecting optimum slat angle in each solar radiation region as shown in Figure 3 (Oh 2011, 2012).

The developed optimum slat angles minimizing the total energy consumption and removing the glare in each solar radiation region follow the regression equations (1) and (2) in cooling and heating modes, respectively (Oh 2011, 2012).

$$f_{(X,Cooling)} = 5E-07x^3 - 0.0008x^2 + 0.448x - 16.771 \quad (1)$$

$$f_{(X,Heating)} = 4E-07x^3 - 0.0006x^2 + 0.352x - 29.087 \quad (2)$$

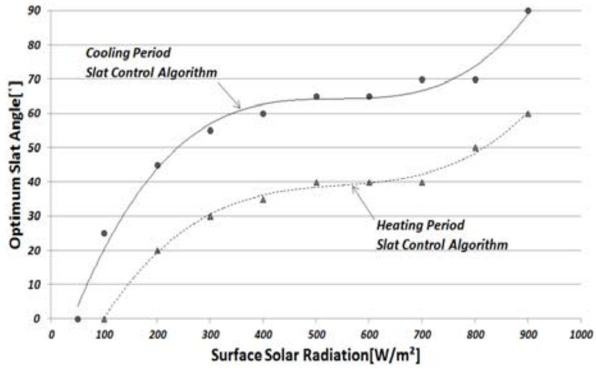


**Figure 3. Slat angle control algorithm in heating and cooling modes (Oh 2011, 2012)**

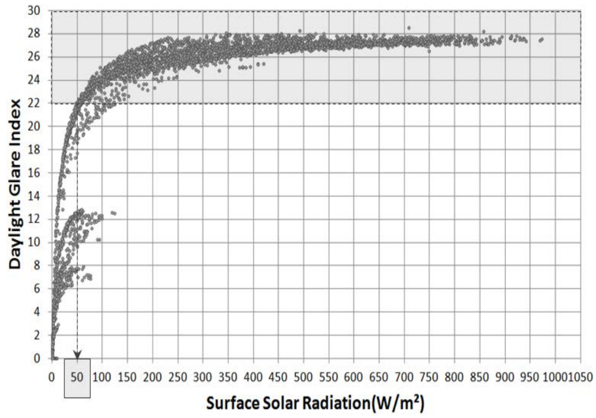


**Figure 4. DGI analysis in each vertical solar radiation without blind operation (Oh 2011, 2012)**

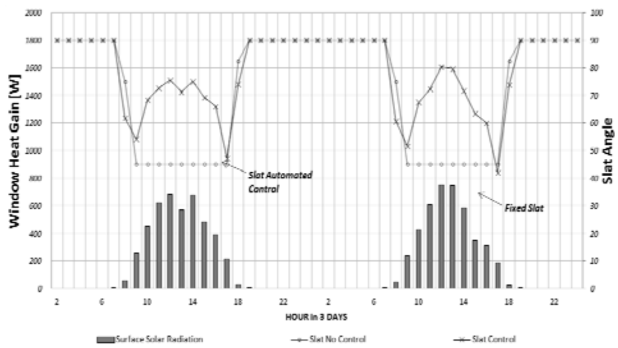


**Figure 5. Slat angle variation in the typical summer days (Aug. 29th ~ 30th) (Oh 2011, 2012)**

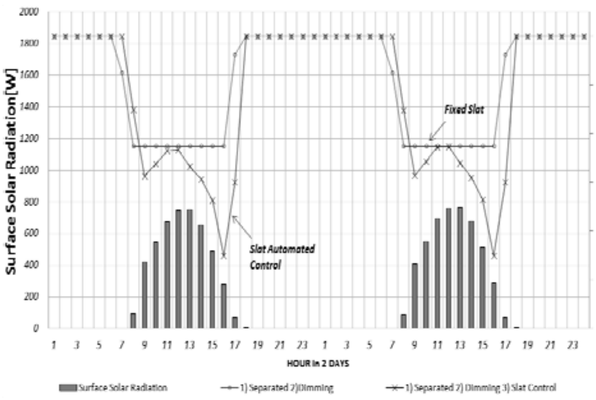


**Figure 6. Slat angle variation in the typical winter days (Jan. 30th ~ 31st) (Oh 2011, 2012)**

In addition, it is necessary to adjust the slat-type blind into upward position under low solar radiation condition for the lighting energy reduction by maximizing the daylight introduction into the space. However, the DGI should be quantitatively evaluated even under the low solar radiation condition due to the possible glare occurrence. Therefore, the additional analysis was performed in this study to decide the solar radiation regions which do not cause the glare in the upward blind position (Oh 2011, 2012).

As a result of the analysis, the solar radiation region less than 50 W/m$^2$ did not show the DGE exceeding 22 as shown in Figure 4. It could be derived from the analysis that there would be no glare even in the upward position of the slat blind under the solar radiation conditions less than 50 W/m$^2$ (Oh 2011, 2012). Therefore, the suggested control strategy of the slat-type blind in this study is to adjust the slat angle in the downward position under the solar radiation greater than 50 W/m$^2$, while placing the slat angle in the upward position under the solar radiation less then 50W/m$^2$ (Oh 2011, 2012).

Figures 5 and 6 show the verification of whether or not the slat angle is properly controlled based on the developed control algorithm under each solar radiation in the typical summer and winter days. As illustrated in the figures, the slat angle was properly adjusted with regard to the solar radiation variations based on the developed 2nd stage control strategy (Oh 2011, 2012).

## RESULTS AND DISCUSSIONS

### Energy performance

After implementing the developed control strategy of the venetian blind, the energy performance was quantitatively evaluated under different conditions of lighting dimming control, blind type, and blind control strategies, given the complete removal of the glare (Oh 2011, 2012). The summary of the different simulated cases are provided in Table 3. In the table, double-sided blind applies different reflectance between front and back sides of the slat and fully rotates the slat when the system mode is switched between heating and cooling mode with the slat angle always fixed at 45°, i.e., up/down control expressed in Table 3.. The double-sided blind has a high reflectance on the front side so that it can reflect direct solar radiation and prevent it from warming the room, while it has a low slat reflectance on the back side so that it can prevent diffuse solar radiation from penetrating the room during the summer, and vice versa during the winter (Oh 2011, 2012). Slat angle control in Table 3 indicates the control strategy described in the previous session.

Table 3. Summary of the simulated cases (Oh 2011, 2012)

| Case | Blind type | Dimming control | Blind control |
|---|---|---|---|
| (1) | No blind | No | No |
| (2) | Double-sided blind | Yes | Slat angle |
| (3) | Double-sided blind | Yes | Up/down |
| (4) | Single-sided with slat reflectance of 0.9 | Yes | No |
| (5) | Single-sided with slat reflectance of 0.5 | Yes | No |
| (6) | Single-sided with slat reflectance of 0.1 | Yes | No |

Table 4. Heating, cooling and lighting loads of the simulated cases (Oh 2011, 2012)

| Case | Lighting (kWh) | Cooling (kWh) | Heating (kWh) | Total (kWh) | Relative percentage |
|---|---|---|---|---|---|
| (1) | 1,939 | 4,529 | 1,068 | 7,536 | 100% |
| (2) | 1,076 | 2,986 | 1,271 | 5,332 | 71% |
| (3) | 1,162 | 3,342 | 1,178 | 5,683 | 75% |
| (4) | 1,029 | 3,030 | 1,876 | 5,935 | 79% |
| (5) | 1,153 | 4,243 | 1,282 | 6,678 | 89% |
| (6) | 1,361 | 5,428 | 998 | 7,787 | 103% |

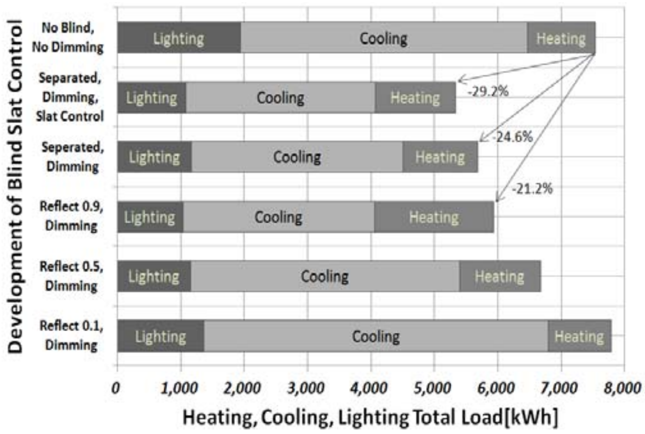


**Figure 7. Load profiles of the simulated cases (Oh 2011, 2012)**

Heating, cooling and lighting loads of the 6 simulated cases are summarized and illustrated in Table 4 and Figure 7, respectively. The case with the slat angle control strategy of the slat blind (Case 2) showed the total load reduction of 29.2% compared to the baseline case without blind installation and dimming control (Oh 2011, 2012).

**Visual comfort**

In this sub-section, the visual comfort performance of the suggested slat angle control strategy aimed at the complete removal of the glare was evaluated for the development of the optimum slat angle control logic. The results are presented in Figure 8. As shown in Figure 8, the glare occurrence of the suggested slat angle control strategy was only 0.1%, indicating that it could completely remove the glare (Oh 2011, 2012).

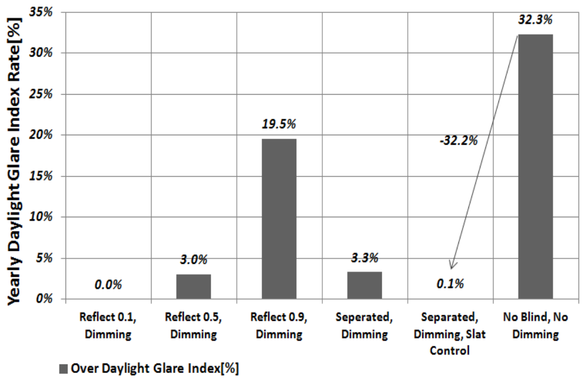


**Figure 8. Percentage of the annual occupied hours exceeding recommended DGI of 22 (Oh 2011, 2012)**

Table 5. The suggested control strategy of the venetian blind (Oh 2011, 2012)

| Field | Description |
|---|---|
| Slat angle control | Optimum slat angle control completely removing the glare and minimizing the total building load |
| Up/down control | Greater than 50W/m$^2$ : Downward position<br>Less than 50W/m$^2$ : Upward position<br>(The maximum solar radiation penetration causing no glare is 50W/m$^2$) |

This control strategy is defined as “slat angle and up/down control of the double-sided blind depending on the solar radiation condition integrated with the linear lighting dimming control” as summarized in Table 5. As shown in the simulated results thus far, the developed control logic of the venetian blind in this study showed greatly improved performance in terms of the total load and visual comfort, indicating that it can significantly enhance the energy efficiency of buildings and the visual comfort of occupants (Oh 2011, 2012).

## CONCLUSION

In this study, the automated control strategy of the venetian blind aimed at the building energy saving and the improved visual comfort is developed.

It turned out that the double-sided blind without dimming control can reduce the total building load by 6.4% compared to the baseline case without blind installation and dimming control and that the double-sided blind integrated with the dimming control can reduce the total building load by 24.6% compared to the baseline case (Oh 2011, 2012). In addition, the optimum slat angle control strategy was suggested which can achieve both the energy saving and the complete removal of the glare. It turned out that the newly suggested control logic can reduce the total building load by 29.2% compared to the baseline case and that the glare occurrence ratio was only 0.1%, indicating that it can completely remove the glare when properly designed and operated (Oh 2011, 2012).

In conclusion, the advanced control strategy suggested in this study showed greatly improved performance in terms of the total load and visual comfort, indicating that it can significantly enhance the energy efficiency of buildings and the visual comfort of occupants in practice (Oh 2011, 2012).

## ACKNOWLEDGEMENT

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