Fundamental Study on the Optimal Design of a Folding Shading Device: Solar Radiation Model & Potential Cooling Load Saving

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Abstract
This study was performed to evaluate the thermal performance of a Folding Shading Device (FSD), focusing on analyzing the effects of cooling load reduction through computer simulation for the system when it is installed on the south facing wall of a building. The results demonstrate that the use of the FSD allows simultaneous consideration of the altitude and azimuth of the sun, while the projected length of the shade can also be adjusted. A mathematical model for the calculation of the shaded area provided by the FSD by considering the size of the fittings was therefore suggested. In addition, the performance evaluation revealed that the installation of existing types of horizontal, vertical, and lattice shading devices installed for the cooling period in a building would lead to the reduction ratios of solar radiation of 17.45-46.98%, 4.70-14.77%, and 26.17-75.17%, respectively. However, the FSD showed the greatest reduction ratio of 22.15-61.74%. In addition, the reduction ratios of cooling loads for the existing horizontal, vertical, and grating shading devices were 6.72-17.23%, 1.68-5.46%, and 10.08-26.89%, respectively, while the FSD achieved the greatest reduction ratio of 8.40-21.85%. Therefore, if the FSD suggested in this study is applied to a building, it can be expected to achieve reductions of the cooling load, thus contributing to the reduction of greenhouse gas emissions.

Keywords: Fold Shading Device; cooling load; altitude; azimuth; solar radiation

1. Introduction
1.1 Study Background and Purpose
Exterior shading devices in buildings are one of the passive systems used to reduce energy load by controlling solar radiation. To allow effective adjustment of the solar radiation when designing an exterior shading device, both the altitude and azimuth of the sun need to be considered. However, because only the altitude or sun is considered in existing shading devices, they are limited because the change of solar radiation per hour cannot be effectively controlled. In addition, because the annual projected length is fixed, their operation according to the season becomes problematic.

Therefore, this study suggested a folding shading device (FSD) which can not only allow simultaneous consideration of the altitude and azimuth of the sun under domestic solar radiation conditions, but can also control the projected length of the shaded area. Such an FSD can reduce solar radiation more effectively than the existing devices, making it more effective at reducing the cooling and heating loads.

Especially, it can be used as a design element for the building skin. This device can also be used with building integrated photovoltaics (BIPV), increasing the practicality of the shading device even further.

1.2 Method and Scope
The method and scope of this study are as follows. First, the problems regarding the existing shading devices were analyzed through a review of the domestic and overseas research literature. After analyzing the derived problems, the design of an FSD that can address the problems was suggested, along with the concept of the FSD and its operation methods by season.

Particularly, a mathematical model was suggested for the calculation of the shading area from the installation of the FSD, and the indoor solar heat gain and cooling load reduction achieved by this shading effect were reviewed in a quantitative way.

The final goal of this study is to develop the design of an FSD that can also reduce energy consumption of cooling and lighting, and can respond to outdoor environmental changes such as solar radiation.
2. Analysis of Literature and Advanced Study on Shading Devices

Various advanced studies have been carried out on exterior shading devices. A.K. Athienitis suggested application methods for various shading devices, especially focusing on the theory and installation methods for the application of daylight shading\(^\text{13}\). H. Koster also presented a variety of technologies for shading devices, their basic concepts, and cases of application\(^\text{14}\). In particular, Norbert Lechner described the basic concepts of various shading devices that can be used in buildings, suggesting a number of methodologies that could provide shading effects through the use of natural elements\(^\text{15}\). In addition, the international standard, ISO/DIS 15099, and the user's manual of the THERM & WINDOW program developed by (Lawrence Berkeley National Laboratory) in the U.S., describe the correlation between window and shading devices, along with their theory and installation methodology\(^\text{16-17}\). Many experimental studies on the use of shading devices for multiple purposes have also been conducted recently, including an examination of a shading device integrated with photovoltaics\(^\text{18-20}\). In Korea, design studies have mostly been conducted for the exterior shading devices of buildings and for the evaluation of solar radiation and sunlight reflection performance of horizontal and vertical shades\(^\text{1}\text{1-23}\). Recent attention has also been given to a different approach to that of the existing shading devices, whereby the exterior shading device is installed separately on the exterior of buildings to serve the dual purposes of providing shade and ventilation\(^\text{14-15}\). In addition, methodological studies to introduce shading devices on super high-rise buildings and to provide daylight using indoor light shelves have been conducted\(^\text{24-29}\). As a result of reviewing the local and international advanced studies on shading devices, it was concluded that similar studies on the FSD suggested herein have not been conducted, to the best of the author's knowledge.

3. Folding Shading Device

3.1 Principle and Concept of Shading Device

Since both the altitude and azimuth of the sun are considered simultaneously with an FSD, it should be a movable shading device, such as a gliding grate, which can be used to effectively block the solar radiation according to hourly changes. Thus, it has the advantage of both reducing and increasing solar radiation depending on the season, because it can shield as much solar radiation as possible in the summer time, but minimize the projected length of the shading device during winter. To install the FSD on a building, horizontal and vertical frames to equip the horizontal and vertical shades should first be installed with separation distances to the opening (F, G, C', D' in Table 3.). In addition, to adjust the projected length of the horizontal and vertical shading devices through the shading angle...
(θ), a revolving screen must be installed at the bottom of the vertical frame. The materials and forms of the shading slot to block solar radiation differ according to the user, but it should basically be designed in a way that the horizontal and vertical slots, determining the angle of shade (θ), move at the same time. The basic concept of the FSD and operating methods in the summer and winter are illustrated in [Fig.1.].

3.2 Mathematical Model of Solar Shading

The shape of the shading area when the FSD is installed on a building is either a parallelogram or a trapezoid, according to the altitude and azimuth of the sun. Therefore, to calculate the shading area, the vertical shading length, determined by the altitude of the sun, and the horizontal shading length, determined by the azimuth of the sun, should be calculated at the same time(30).

3.2.1 Vertical Shading Length according to Altitude of Sun

The vertical shading length according to the altitude of the sun can be calculated using the vertical lengths of the shade and window, angle of the shade, projected length, and altitude of the sun. The calculation methods are shown in Eq. (1)-(4) ([Fig.2.] and [Fig.3.]).

\[ D = C \times \cos \theta \]  
\[ A = C \times \sin \theta + I \]  
\[ J = E + F - (C - D) \]  
\[ K = J - (A + H) \times \tan \theta \]  

3.2.2 Horizontal Shading Length according to Azimuth of Sun

The horizontal shading length cast by the FSD should be calculated by first dividing the FSD into upper and lower parts. The upper and lower horizontal shading lengths according to the shading device can be estimated using the horizontal lengths of the shade and window, azimuth of the sun, and can be calculated using Eq. (5)-(9) ([Fig.4.] and [Fig.5.]).

\[ G = (A + H) \times \tan \gamma \]  
\[ F = (B + D) - G \]  
\[ B = \frac{X}{\tan \alpha} \]  
\[ H = (B - H) \times \tan \gamma \]  
\[ E = (B + D) - H \]  

Fig.2. Concept Map for Calculation of Vertical Shading Length with FSD

Fig.3. Method for Calculating Vertical Shading Length with FSD

Fig.4. Concept Map for Calculation of Horizontal Shading Length with FSD

Fig.5. Method for Calculation of Vertical Shading Length in Upper and Lower Parts of FSD

3.3 Shading Area

Based on the results of the above calculations, the shading area provided by the installation of the FSD can be calculated using Eq. (10).

\[ A_2 = K \times \frac{E + F}{2} \]  

(10)
4. Evaluation of Performance of Folding Shading Device

4.1 Overview of Computer Simulation

To evaluate the solar radiation performance of the FSD, a computer simulation was used to compare the solar radiation and cooling load reduction effects of horizontal, vertical, and grating shading devices, which are the typical forms of shading, with those of the FSD during the summer period. For the computer simulation program, the IES_VE (Integrated Environmental Solutions _ Virtual Environment) program was used, which can predict the environmental performance of a building. In addition, the weather data, shape and type of the building were applied in the same way. The computer simulation was conducted using the types of shading devices and projected length as variables.

4.2 Modeling and Characteristics of Building

The setting of the model for simulation was assumed to be a residential building with a single floor. In addition, the insulating performance of the windows and walls, the indoor heating and cooling temperatures, and the air change rates were applied according to the criteria regulated in domestic and overseas building Acts.

4.3 Modeling and Characteristics of Shading Device

The characteristics of the horizontal, vertical, and grating shading devices, as well as the FSD applied to the building are described in [Table 3.] below.

Table 1. Summary of the Building Modeled in the Simulation Program

| Properties of building | Incheon, Korea |
|------------------------|---------------|
| Location               |               |
| Latitude               | 37° 29′       |
| Longitude              | 127° 38′      |
| Size of building       | 10.0m × 10.0m |
| Area of floor          | 96.4 m²       |
| use of building        | Residence     |
| Level of building      | 4.0 m         |
| Size of window         | 4.0m × 2.0m   |
| Direction of window    | South         |

Table 2. Structure and Properties of the Walls

| No. | Material  | Thickness mm | U-factor W/m²-K |
|-----|-----------|--------------|-----------------|
| 1   | Concrete  | 200          |                 |
| 2   | Insulation| 60           | 0.485           |
| 3   | Air       | 50           |                 |
| 4   | Hard-board| 10           |                 |
| 1   | Felt      | 12           |                 |
| 2   | Concrete  | 150          |                 |
| 3   | Insulation| 60           | 0.409           |
| 4   | Air       | 50           |                 |
| 5   | Plaster   | 9.50         |                 |
| 1   | Concrete  | 150          |                 |
| 2   | Insulation| 80           |                 |
| 3   | Gravel    | 150          | 0.381           |
| 4   | Soil      | 250          |                 |

4.4 Performance Evaluation

In the performance evaluation of the FSD, the solar heat gain and cooling load of the building without using a shading device were employed as the standard. When the horizontal, vertical, lattice, and folding shading devices were installed in the building, their solar heat gains and reduction ratios of cooling loads were analyzed and compared to those for the standard building.
(1) Analysis of Solar Heat Gain

In the building without a shading device, the total solar heat gain per year was determined to be 3.33 MW and the total solar heat gain during the cooling period (May-October) was determined to be 2.38 MW. Furthermore, when the horizontal, vertical, and lattice shading devices with the projected length of 1.1 m ($\theta=10^\circ$) were applied to the standard building, the solar heat gains of the building during the same period were found to be 1.23 MW, 1.42 MW, and 1.10 MW, respectively. However, the solar heat gain was 1.16 MW, a little higher than that for the lattice shading device when the FSD with the equal projected length was installed on the standard building; these patterns for solar heat gain of the building were identical when the projected lengths of each shading device were increased continuously. As a result of analyzing the patterns on the reduction ratio of solar heat gain of the FSD, the reduction ratio was found to rapidly increase up to the projected length of the shade at 3.8 m ($\theta=50^\circ$), whereas it drastically decreased for projected lengths of 3.8 m or higher. This was thought to be because the angles of the FSD above 50$^\circ$ would block almost all windows that might absorb solar radiation. In addition, it was determined that although both the altitude and azimuth of the sun are considered with the existing grating shading device, the FSD was more effective at blocking solar radiation during the summer season ([Table 5.] and [Fig.6.]).

(2) Cooling Load Analysis

The analysis of the cooling load was applied in the same way as that for determining the amount of solar gain. In other words, the reductions in cooling load that would be obtained if horizontal, vertical, and grating shading devices, as well as the FSD, were applied to the building were calculated and compared to the standard building without installation. As a result, it was determined that the annual total cooling load of the standard building without a shading device would be 2.38 MW. The installation of horizontal, vertical, and grating shading devices with the projected length of 1.1 m ($\theta=10^\circ$) were found to result in the cooling loads of 2.22 MW, 2.34 MW, and 2.14 MW, respectively. However, the FSD cooling load was 2.18 MW.

Table 5. Solar Heat Gain during Cooling Period

|       | 10$^\circ$ | 20$^\circ$ | 30$^\circ$ | 40$^\circ$ | 50$^\circ$ | 60$^\circ$ | 70$^\circ$ | 80$^\circ$ | 90$^\circ$ |
|-------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| Non-Device | 1.49      | 1.49      | 1.49      | 1.49      | 1.49      | 1.49      | 1.49      | 1.49      | 1.49      |
| FSD     | 1.16      | 0.95      | 0.83      | 0.73      | 0.66      | 0.62      | 0.60      | 0.58      | 0.57      |
| Grating | 1.10      | 0.88      | 0.71      | 0.57      | 0.49      | 0.43      | 0.40      | 0.37      | 0.37      |
| Horizontal | 1.23    | 1.07      | 0.99      | 0.91      | 0.86      | 0.83      | 0.81      | 0.80      | 0.79      |
| Vertical | 1.42      | 1.37      | 1.34      | 1.31      | 1.29      | 1.28      | 1.27      | 1.27      | 1.27      |
Table 6. Annual Cooling Load by Installation of Each Shading Device

| Device   | 10°    | 20°    | 30°    | 40°    | 50°    | 60°    | 70°    | 80°    | 90°    |
|----------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
|          | Total  | Total  | Total  | Total  | Total  | Total  | Total  | Total  | Total  |
|          | Cooling load (MW) | Cooling load (MW) | Cooling load (MW) | Cooling load (MW) | Cooling load (MW) | Cooling load (MW) | Cooling load (MW) | Cooling load (MW) | Cooling load (MW) |
| Non-     | 2.38   | 2.38   | 2.38   | 2.38   | 2.38   | 2.38   | 2.38   | 2.38   | 2.38   |
| FSD      | 2.18   | 2.05   | 1.99   | 1.93   | 1.90   | 1.88   | 1.87   | 1.86   | 1.86   |
| Grating  | 2.14   | 2.01   | 1.92   | 1.85   | 1.81   | 1.78   | 1.76   | 1.75   | 1.74   |
| Horizontal | 2.22   | 2.12   | 2.07   | 2.03   | 2.00   | 1.99   | 1.98   | 1.97   | 1.97   |
| Vertical | 2.34   | 2.31   | 2.29   | 2.27   | 2.26   | 2.26   | 2.25   | 2.25   | 2.25   |

MW, representing an 8.40% reduction ratio compared to the standard building. In addition, as the projected length was increased continually, the reduction ratio of the cooling load for FSD showed a continuous increasing trend, up to 21.85% reduction of the cooling load ([Table 6.] and [Fig.7.]).

5. Conclusion

In this study, a Folding Shading Device (FSD) was suggested, and the reduction of solar heat gain and cooling load were then analyzed and compared with other devices through simulation. The results are summarized as follows.

1) With the FSD, the altitude and azimuth of the sun can be considered simultaneously, and the projected length can also be adjusted. Therefore, a mathematical model was suggested to allow calculation of the shaded area offered by the FSD by considering the size of the fittings.

2) The performance evaluation through simulation resulted in the following observations. First, the ranges of the amounts of solar radiation reduction when existing horizontal, vertical, and grating shading devices were installed in a building were found to be 17.45-46.98%, 4.70-14.77%, and 26.17-75.17%, respectively. However, the FSD showed the greatest reduction ratio, with a range of 22.15-61.74%. In addition, the cooling load reduction ratios for the existing horizontal, vertical, and grating shading devices were 6.72-17.23%, 1.68-5.46%, and 10.08-26.89%, respectively, while the FSD displayed the greatest cooling load reduction ratio of 8.40-21.85%.

3) If the FSD suggested in this study is applied to a building, it can be expected to provide reductions to the cooling load, contributing to the reduction of greenhouse gas emission.35-37

This study was performed to establish the methodological model of FSD (Folding Shading Device) and to analyze the potential for reducing cooling load by its installation to a building. In future research, a study will be performed for the design of slots, which can introduce daylight to inside through FSD, using solar radiation reflected from the sky and the ground, and for the durability of FSD, to endure outdoor environmental conditions such as strong winds, storms, and typhoons.

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