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A Study on the Blind-Type Light Shelf System for Improvement of Indoor Uniformity Ratio of Illuminance

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ABSTRACT

Purpose: Light shelf systems can reduce the energy required for lighting by facilitating natural light ingress deep into a building. However, while they reflect a large amount of light into the building, they tend to create a low uniformity ratio of illuminance, and their indoor illuminance is not adjustable. Also, they are seldom used in architectural design due to their aesthetic disadvantages. This study proposes a blind-type light shelf system, consisting of multiple light shelf slats and blind slats, in order to solve the lighting problem of the light shelf system by modifying it with a blind system to reduce the energy required for artificial lighting. **Method**: Three combinations of blind-type light shelf system (no light shelf, 50 mm slats, and 100 mm slats) were proposed, and their performance was evaluated based on illuminance and uniformity ratios achieved in the indoor environment. **Results**: Case 2(50 mm slat) slatshowed an improvement, compared to the unmodified window, of up to 3.2 times while Case 3(100 mm slat), showed an improvement in the uniformity ratio of up to 2.8 times. With the installation of a blind-type light shelf system, the uniformity ratio can be ~3.2 times higher in the winter solstice and summer solstice, resulting in more light penetrating deeper into the interior of the building. The blind light shelf system was more effective in Case 2 than in Case 3 because it was better to have more light slats, despite the narrow slat width.

KEYWORD

Blind
Light Shelf
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1. Introduction

According to the Global Status Report 2018 of the United Nations Environment Programme (UNEP/IEA 2018), buildings accounted for the largest proportion (30%) of energy-related carbon dioxide emissions. The construction sector is attempting to reduce energy use in buildings through the incorporation of eco-friendly building materials and eco-friendly design. However, existing buildings present difficulties due to their inherent structural and economic problems[1].

With the rapid increase in energy consumption, the construction industry is trialing various measures to prevent energy loss from windows, which make up the largest area of the building envelope. Measures to prevent the loss of cooling and heating energy include colored and low-emissivity (low-E) glass, phase change materials (PCM), and louver and blind systems that reduce cooling and heating energy by controlling illumination. In addition, studies have been conducted on light shelf systems, which reduce the energy required for lighting by introducing natural light deep into a room[2]. The light shelf system can provide sufficient work surface illuminance without using artificial lighting, by increasing the indoor illuminance and its uniformity ratio through the inflow of natural light deep into a room. However, the existing single-slat configuration creates an irregular illuminance with a low uniformity ratio and does not allow much control of the resulting indoor illuminance. Furthermore, light shelf systems are seldomly used in architectural design due to their aesthetic and morphological limitations[3].

To improve the indoor uniformity ratio of illuminance, this study addresses the low uniformity ratio of illuminance created by the light shelf system, by modifying the design with a blind system, in a multi-slat configuration. This study proposes a blind-type light shelf system, composed of multiple light shelf slats and blind slats in a blind slat configuration, and was conducted as follows.

First, the theories and characteristics of the elements comprising the proposed system were established through literature review. Second, the configuration, system design, and operation methods of a blind-type light shelf, combined with a double-skin system, were proposed. Third, a testbed was set up to verify the proposed systems and their efficiencies were verified in a realistic light environment.

To verify how the performance of the proposed light shelf

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systems varied in response to slat width, we analyzed the typical indoor illuminance, uniformity ratio of illuminance, and backside illuminance values created by the different systems, under daylight conditions at the winter solstice and summer solstice. Three different window systems were tested: no light shelf, 50-mm-slat light shelf, and 100-mm-slat light shelf.

2. Theoretical Considerations for Improvement of Indoor Lighting Performance

2.1. Natural lighting and indoor illuminance standards

In architecture, the incorporation of natural lighting is beneficial to good illuminance for indoor spaces. Designing a building envelope with voids can create a comfortable visual environment by actively using natural light and allows the suggestion of various types of architectural spaces. Appropriate blocking of natural light in summer reduces the cooling load, while allowing more inflow of natural light in winter can reduce the power consumption of a building. Both cases provide economic benefits through energy reduction.

Furthermore, appropriate natural lighting can improve the eye comfort of indoor occupants and improve work efficiency. Furthermore, natural lighting is an important factor to consider in architectural planning because it creates a visual connection with the exterior of the building and can even affect the mental health of occupants[4].

The illuminance standards of the Korean Industrial Standards (KS) specify the most comfortable reference illuminances for people, according to different spaces and activities. According to the housing sector standards, illuminance values of 300 to 600 lx are required for the living room, bed room, and kitchen, which are the main activity spaces of occupants and closely related. For indoor activities, 400 lx is considered the average illuminance for people to feel most comfortable and concentrate on activities[5].

Table 1. KS Reference Illuminance Table Illuminance Range

Space/Activity	Optimal Illuminance (lx)
Living Room	300-400-600
Bedroom	300-400-600
Kitchen	300-400-600
Study	600-1000-1500
Reading, Make-Up	300-400-600
Meal, Party	60-100-150

Table 2. Recommended Uniformity Ratio of Illuminance

Space/Activity	Uniformity Ratio of Illuminance
Skylight	Over 0.3
Daylight Lighting	Over 0.1
Artificial Lighting	Over 0.17

The uniformity ratio of illuminance indicates the uniformity of light on the work surface and is used as an evaluation index of the illumination environment. The uniformity ratio of illuminance is calculated as follows[6]:

$$Uniformity\ ratio\ of\ illuminance = \frac{Minimum\ illumnance\ (Emin)}{Average\ illuminance\ (Eave)} \quad \text{(Eq. 1)}$$

2.2. Light shelf functions

The function of the light shelf system is to evenly distribute light entering through a building's windows and to introduce that light deep into the indoor spaces. The daylight reflects off the surface of the light shelf and is then reflected again from the ceiling. In this way, light flows into a room and provides a more evenly distributed brightness in the indoor. Another role of the light shelf is to reduce the direct inflow of sunlight into a room, which causes glare and leads to the deterioration of work efficiency, by blocking natural light from outside and reflecting it to the ceiling.

Light shelves are largely classified into three types: outdoor, indoor, and mixed-form light shelves. The outdoor light shelf is most advantageous for blocking direct radiation from high solar altitudes, but disadvantageous for the outside view of a building. The indoor light shelf is best for enhancing the inflow of natural light and can provide an outside view to some extent. The mixed-form light shelf has the advantages and disadvantages of both the outdoor and indoor light shelves[7].

2.3. Blind functions

Blinds are the most commonly used awning device in residential and office buildings and are used to block sunlight and to reduce glare. There are three types of blinds: vertical, venetian, and roll blinds. Depending on the slat material, they are also classified into wood, aluminum, and other materials.

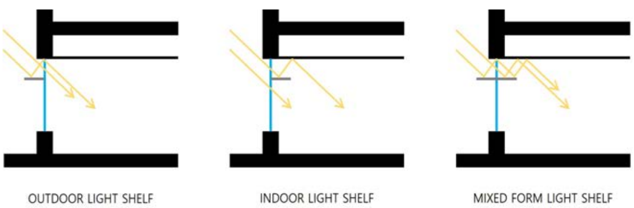


Fig. 1. Type of Light Shelf

Fig. 2. Type of Blinds

Typically, blinds cover the entire window area, and allow for the adjustment of window coverage and slat angle through a simple mechanism. Furthermore, blinds can control the amount of insolation, protect the privacy of indoor occupants, and secure a certain degree of external view. By adjusting the solar radiation inflow, blinds can prevent an increase of the indoor temperature in summer and can also block glare for occupants. In addition, blinds allow for flexibility in planning the envelope of a building because they can be installed both inside and outside of the envelope. When blinds are installed inside, anyone can easily install and remove them, as required[8, 9].

2.4. Sub-Conclusion

In this chapter, we examined the theories of natural lighting and indoor illuminance standards and reviewed the functionality of light shelves and blinds in prior studies.

Both light shelves and blinds are made of slats. Double light shelves are popular, and are comprised of at most two slats, whereas blinds are produced according to the size of window and comprise multiple slats. Thus, the ratio of the occupied window area is different according to the function. Although they have different purposes, such as the inflow and blocking of light, in both systems the slats serve the main function, and it seems that these two functions can be interconnected.

Therefore, we propose a blind-type light shelf system which uses multiple slats, instead of the limited slats of an ordinary light shelf, to provide optimal indoor illuminance.

3. Blind-type Light Shelf Performance Evaluation Method for Improvement of Lighting Performance

3.1 Method and Environment for Performance Evaluation

A testbed was constructed, with a width of 4.9 m, a height of 2.4 m, and a depth of 2.5 m, to evaluate the performance of the double-skin system with a blind-type light shelf, in relation to the standards outlined in Table 2. The light shelf double-skin system attached to a window with a width of 1.6 m and a height of 1.8 m. In addition, the artificial light environment was equipped with an artificial solar irradiation device, set up outside the window on which the light shelf system was installed.

The experimental light environment was equipped with a solar simulation system which produced parallel rays on a spectrum with the same color rendering index, color temperature, and brightness as those of natural light at 2 p.m. in clear weather. In addition, the insolation intensity was freely adjustable through the angle, height, and lamp controls of the solar simulation system [10].

Table 3. Summary of testbed model

Testbed Specifications	
Room size, Material	- 4.9 m (W) x 6.6 m (D) x 2.5 m (H) - Reflexibility: Ceiling (86%), Wall (46%), Floor (25%)
Window size, material	- 1.6 m (W) x 1.8 m (H) - Type: Pair glass 24 mm (6 mm+12 mm+6 mm), Transmissivity (80%)
Illuminance sensor	- Sensing element: Silicon photo sensor with filter - Detection range: 0~200,000 lx - Precision: ±0.3%
External illuminance	- Summer: 70,000~80,000 lx - Winter: 20,000~30,000 lx
Direction	- South Aspect
Picture	

Table 4. Summary of Solar Simulation System

Summary of Solar Simulation System	
Lamp Type	Metal halide lamp *120EA
Average Radiation	>1000 W/㎡
Uniformity	> 15%
Wavelength Range	300~2500 nm
Spectral Agreement	C class
Temperature Range	0~35 ℃
Picture	

By adjusting the height, angle, and amount of light, the solar simulation system could be set to different daylight conditions representing the period between 10 a.m. and 3 p.m. on the summer and winter solstices, as shown in Fig. 3. The illuminance of the solar simulation system were set to 70,000 lx and 20,000 lx for 10 a.m. on the summer and winter solstice, respectively, and to 80,000 lx and 30,000 lx for 12 p.m. on the summer and winter solstice, respectively. The median altitude on the summer solstice was set to 60° at 10 a.m. and 76.5° at 12 p.m., and on the winter solstice, to 19.5° at 10 a.m. and 29.5° at 12 p.m.[11].

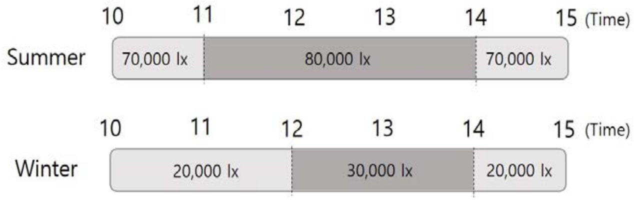


Fig. 3. Daylight Condition Settings

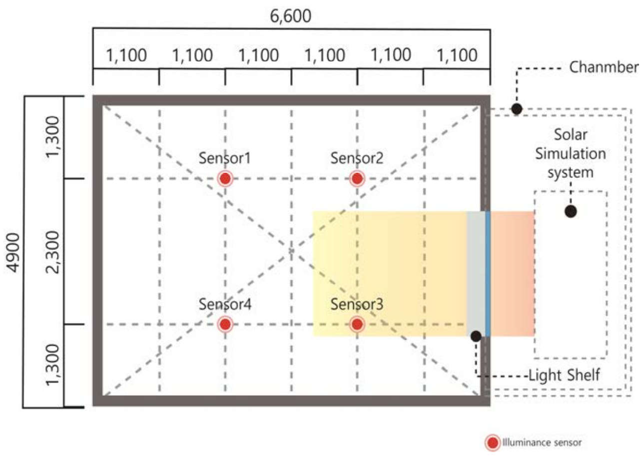


Fig. 4. Plan and Section of Illumination Sensor

Four illumination sensors were installed, using the four-point method of the IES, at a height of 750 mm from the ground, which is the common desk height for human activities in indoor residential environments. The window was not installed in a central position because the testbed was based on a residential bedroom environment. Consequently, the solar simulation system was set up in such a way that the light would come through the window.

The illuminance value was measured for each width of the light shelf slats, at 10° increments between −30° (slat tilted toward the solar simulation system) and 30° (slat tilted toward the room) [12]. Furthermore, the average indoor illuminance value and the uniformity ratio of illuminance are required to determine the optimal illuminance environment. Thus, the average of the four illumination sensor values was obtained, and the uniformity ratio of illuminance was then determined using this value.

3.2. Characteristics of the proposed blind-type light shelf system

The slat configuration was derived from a previous study on the lighting performance of a system incorporating an external light shelf and an internal blind.

The light shelf slat was installed 1.2 m above the floor, and the blind slat was installed below it. A reflective film with a reflectivity of 98% was attached to the light shelf slat, and the blind slat was composed of white aluminum[13].

The blind-type light shelf system is operated in the same way as a manual blind, for convenience in existing homes, and was designed to allow for performance comparison between different sizes and spacing of slats, and width of the light shelf.

Table 5. Blind-Type Light Shelf System

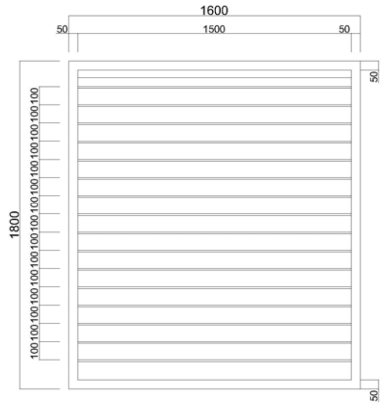
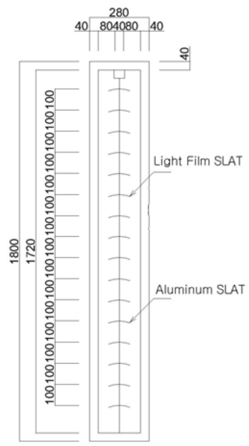
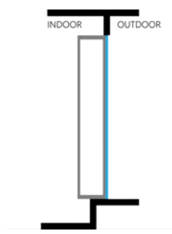
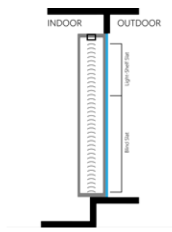
Blind-Type Light Shelf System	
Light Shelf Plan	
100 mm Slat Section Detail	

Table 6. Light Shelf Cases - 1

Case	Picture	Section
Case 1 (Unmodified window)		
Case 2 (50 mm)		

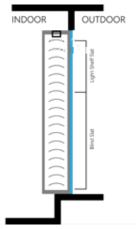
Case	Picture	Section
Case 3 (100 mm)		

Table 7. Light Shelf Cases - 2

	Case 1	Case 2	Case 3
Slat Width (mm)	N/A	50 mm	100 m
Slat Angle (°)		180°	
Height (mm)		1800 mm	
Mirror Film Reflectivity (%)		98%	

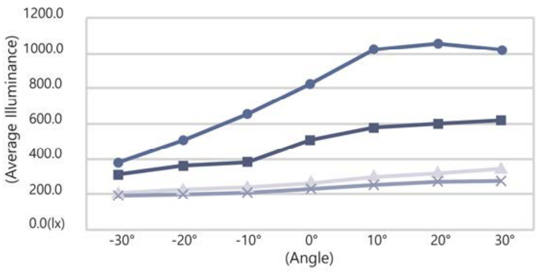
Three cases of the blind-type light shelf system were evaluated, with the parameters shown in Tables 4 and 5. They were classified by the slat width of the blind to which a light shelf was attached. Case 1 was an unmodified single-skin window. Case 2 and Case 3 combined a double-skin window with blind-type light shelf system, with respective slat widths of 50 mm and 100 mm. In addition, every slat was permitted a rotation of 180° and could simultaneously move up or down, allowing users to easily control the amount of light coming into the room.

4. Performance Evaluation of Blind-type Light Shelf

4.1 Deriving the optimal angle for the 50 mm slat blind-type light shelf

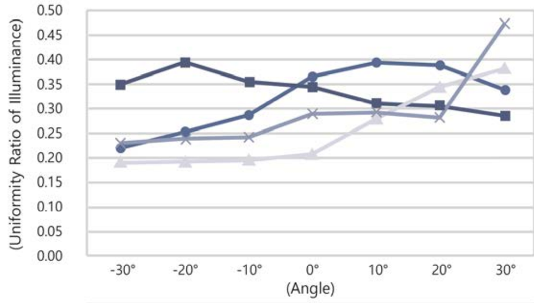
A blind-type light shelf with a 50 mm slat resulted in following average illuminance and uniformity ratios of illuminance values.

Fig. 5. shows that for Case 2, the best illuminance, of 602.6 lx, was achieved with a 20° slat angle at 10 a.m. on the winter solstice,



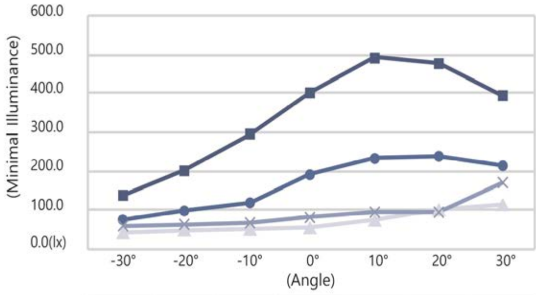
	-30°	-20°	-10°	0°	10°	20°	30°
Winter_AM 10	316.3	360.3	385.3	506.7	576.7	602.6	618.3
Winter_PM 12	385.9	506.6	653.8	829.6	1028.4	1060.1	1016.8
Summer_AM 10	197.5	207.5	215.6	228.8	249.4	269.6	281.6
Summer_PM 12	213.1	230.7	242.3	242.3	301.9	318.3	348.2

Fig 5. Average Illuminance for Case 2 (50 mm Slat Light Shelf)



	-30°	-20°	-10°	0°	10°	20°	30°
Winter_AM 10	0.22	0.25	0.29	0.37	0.40	0.39	0.34
Winter_PM 12	0.35	0.39	0.36	0.34	0.31	0.31	0.29
Summer_AM 10	0.19	0.19	0.20	0.21	0.28	0.35	0.38
Summer_PM 12	0.23	0.24	0.24	0.29	0.29	0.28	0.47

Fig. 6. Uniformity Ratio of Illuminance for Case 2 (50 mm Slat Light Shelf)



	-30°	-20°	-10°	0°	10°	20°	30°
Winter_AM 10	70	91.3	111.3	186.3	232.5	235.5	210
Winter_PM 12	135	200	291.4	401.3	497.5	481.5	395.6
Summer_AM 10	37.4	40	42.2	47.7	69.9	93.5	107.5
Summer_PM 12	49.8	55.3	59.1	76.1	88.6	89.6	165.3

Fig. 7. Minimal Illuminance for Case 2 (50 mm Slat Light Shelf)

while 348.20 lx was achieved with a 30° slat angle at 12 p.m. on the summer solstice. These were the closest values to the 600 lx target illumination value for a work surface in an indoor environment.

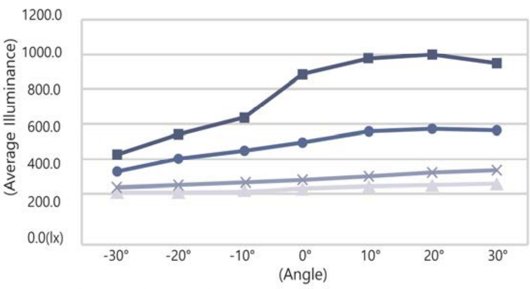
As shown in Fig. 6., the highest uniformity ratios of illuminance, of 0.4 and 0.47, appeared at 10° at 10 a.m. on the winter solstice and at 30° at 12 p.m. on the summer solstice, respectively. These results coincide with the highest minimal illuminance values in Fig. 7. As the indoor backside illuminance value increased through the light shelf, the uniformity ratio of illuminance improved, showing a value that is higher than 0.3 by 0.1 or higher, the standard uniformity ratio of illuminance for artificial lighting. Even though the average illuminance value increased as the light shelf slat moved from 0° toward the indoor space, the backside illuminance increased at a higher rate, thus greatly improving the uniformity ratio of illuminance. However, due to the lower solar altitude and lower sunlight angle on the winter solstice, when the slat was facing inwards in the afternoon, the angle of the lower blind slat was similar to the sunlight angle. Consequently, the light could not be blocked effectively, and the front illuminance increased exponentially, resulting in a decrease in the uniformity ratio of illuminance, which is a disadvantage of having a slat facing inwards. In the afternoon, the solar altitude and angle are lower, so the slat should be directed outwards to ensure light transmission to the indoor backside. Since the average illuminance uniformity ratio is higher the slat angle toward inside, it was more efficient to use different angles for the morning and afternoon of the winter solstice.

Based on the above discussion, on the winter solstice, the best average illuminance and uniformity ratio, of 576.7 lx and 0.40, respectively, is obtained with a slat angle of 10°. On the summer solstice, the optimal average illuminance and uniformity ratio of illuminance, of 348.2 lx and 0.47, respectively, are obtained with a slat angle of 30°. Therefore, the target work surface illuminance can be achieved without artificial indoor lighting when different angles are applied according to the season.

4.2 Deriving the optimal angle for 100 mm slat blind-type light shelf

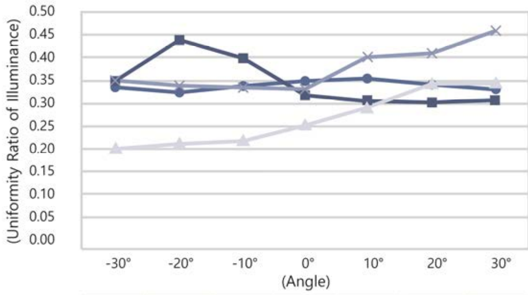
The average illuminance and the uniformity ratio of illuminance obtained with a 100 mm slat, at specific times on the summer winter solstices are described below.

As shown in Fig. 8., when the 100 mm light shelf slats were set to various angles at 10 a.m. and 12 p.m., the illuminance values closest to the 600 lv target value were 632.2 lx, achieved with a −10° slat angle at 12 p.m. on the winter solstice, and 331.8 lx, achieved with a 30° slat angle at 12 p.m. on the summer solstice. As shown in Fig. 9., the highest uniformity ratios of illuminance, of 0.44 and 0.46, were achieved with a −20° slat angle at 12 p.m. on the winter solstice, and a 30° slat angle at 12 p.m. on the summer solstice. These results coincided with the highest minimal illuminance values in Fig. 10. As the indoor backside illuminance value increased through the light shelf, the uniformity ratio of illuminance improved, showing a value that is higher than 0.3 by 0.14 or higher, the standard uniformity ratio of illuminance for artificial lighting. Even though the average illuminance value



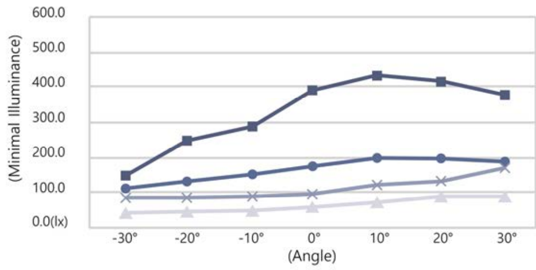
	-30°	-20°	-10°	0°	10°	20°	30°
Winter_AM 10	326.3	406.1	443.1	492.5	559.4	573.8	563.5
Winter_PM 12	422.2	536.2	632.2	887.2	976.7	997.2	947.5
Summer_AM 10	208.5	208.7	216.8	226.3	240.2	252.3	256.7
Summer_PM 12	235.2	250.3	261.9	279.2	299.8	319.5	331.8

Fig. 8. Average Illuminance for Case 3(100 mm Slat Light Shelf)



	-30°	-20°	-10°	0°	10°	20°	30°
Winter_AM 10	0.34	0.32	0.34	0.35	0.36	0.34	0.33
Winter_PM 12	0.35	0.44	0.40	0.32	0.30	0.30	0.31
Summer_AM 10	0.20	0.21	0.22	0.25	0.29	0.34	0.34
Summer_PM 12	0.35	0.34	0.33	0.33	0.40	0.41	0.46

Fig. 9. Uniformity Ratio of Illuminance for Case 3 (100 mm Slat Light Shelf)



	-30°	-20°	-10°	0°	10°	20°	30°
Winter_AM 10	110	130	150	172.5	198.8	196.25	187.5
Winter_PM 12	147.5	248.8	287.5	392.5	435.5	481.8	377.5
Summer_AM 10	41.6	43.5	47	57.5	39.6	86.5	87.8
Summer_PM 12	82.5	84.8	87.4	92.2	120.3	130.6	169

Fig. 10. Minimal Illuminance for Case 3(100 mm Slat Light Shelf)

increased as the slat angle changes from 0° to −20°, the backside illuminance increased at a higher rate, thus greatly improving the uniformity ratio of illuminance. However, in the case of the winter solstice, although the uniformity ratios of illuminance were similar, due to the lower solar altitude and sunlight angle than those of the summer solstice, more light is blocked in the morning when the slat is directed more to the outside, so the average illuminance appears to drop. Therefore, facing the slats outwards is considered to be more conducive to optimal work surface illuminance.

Based on the above discussion, on the winter solstice, the best average illuminance and uniformity ratio of illuminance, of 632.2 lx and 0.4, respectively, were obtained with a slat angle of −20°. On the summer solstice, the best average illuminance and uniformity ratio of 331.8 lx and 0.46, respectively, were achieved with a slat angle of 30°. Therefore, work surface illuminance can be achieved without artificial indoor lighting when different slat angles are applied according to the season.

4.3 Comparison of uniformity ratios of illuminance

The uniformity ratios of illuminance obtained for the winter and summer solstices were compared between Case 1

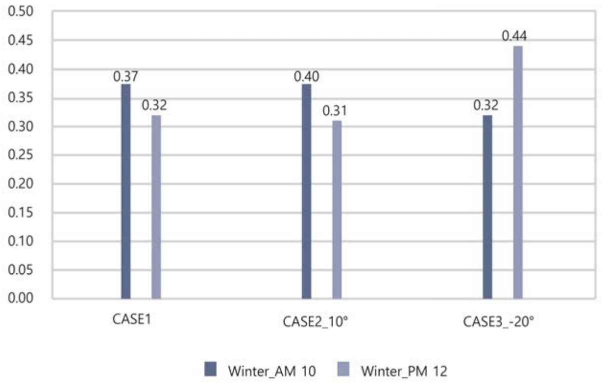


Fig. 11. Uniformity Ratio of Illuminance of Light Shelf in Winter

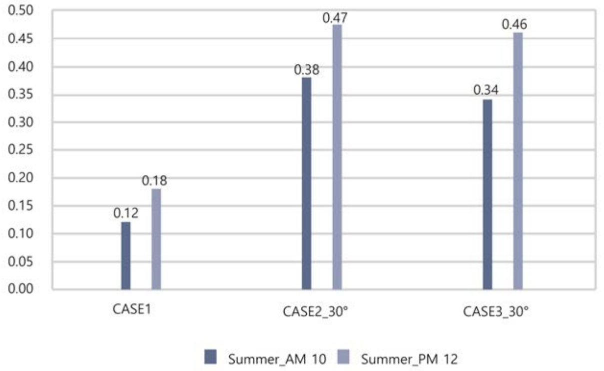


Fig. 12. Uniformity Ratio of Illuminance of Light Shelf in Summer

(uninstalled), Case 2 (50 mm slat light shelf) , and Case 3 (100 mm slat light shelf) at the optimal angle.

Fig. 11. compares the uniformity ratios of illuminance obtained at the optimal slat angles on the winter solstice for Case 1, Case 2, and Case 3. In Case 2, the uniformity ratio of illuminance increased in the morning, but decreased in the afternoon. In Case 3, it decreased in the morning and significantly increased in the afternoon. The reason for this difference is that the slat width of Case 3 is twice that of Case 2, thus showing opposite results in blockage and inflow of light due to the low solar altitude and sunlight angle on the winter solstice.

Fig. 12. compares the uniformity ratios of illuminance of the different cases, obtained at the optimal angles on the summer solstice. In comparing Case 1 and Case 2, the uniformity of Case 2 showed an increase of approximately 3.2 times in the morning and approximately 2.6 times in the afternoon. The uniformity of Case 3 showed an increase of approximately 2.8 times in the morning and approximately 2.6 times in the afternoon. In other words, on the summer solstice, Case 3 showed a higher uniformity ratio of illuminance because the larger slat width greatly contributed to the increase in backside illuminance.

In summary, the blind-type light shelf system of Case 2, which consists of 13 50-mm-wide slats, reflected more light and contributed more to an increase in backside illuminance than Case 3, which consisted of 7 100-mm-wide slats. This suggests that the number of slats plays a more important role than the slat width in the uniformity ratio of illuminance. However, Case 3 also created a slightly brighter indoor environment, as indicated by the average indoor illuminance.

Light shelf systems have an excellent reduction effect on the energy required for indoor lighting, but they do not create a high uniformity ratio of illuminance. Therefore, the blind-type light shelf system proposed in this study can provide a higher uniformity ratio of illuminance and backside illumination to create an excellent illumination environment and a pleasant viewing environment.

5. Conclusions

This study proposed configurations for the light shelf and blind slats of the blind-type light shelf system and evaluated the performance of the system according to slat width. The performance of the proposed system was evaluated using three different experimental setups, with varying slat angles and lighting conditions simulating the winter and summer solstice. The resulting average indoor illuminance, uniformity ratio of illuminance, and backside illuminance values were analyzed.

The maximum uniformity ratio of illuminance for Case 2 (50 mm slat light shelf) was approximately 3.2 times higher than that of Case 1 (no light shelf system installed), while maximum the uniformity ratio of Case 3 (100 mm slat light shelf) showed a further improvement of approximately 2.8 times. When a blind-type light shelf system is installed, the uniformity ratio of illuminance in the winter solstice and the summer solstice can increase by as much as ~2.3 times, allowing the light to penetrate further into the building. The blind-type light shelf system showed better results in Case 2 (50 mm) than in Case 3 (100mm). Because despite the narrow slat width, Case 2 had more light shelf slats, so more light was reflected into the back side of the room and the narrow slat width only blocked a portion of the light. As a result, the excellent uniformity ratio of illuminance, which was the aim of this study, was achieved. Furthermore, an illumination environment close to the ideal working surface illuminance of 600 lx was formed. This demonstrates that the light shelf system can provide a comfortable viewing environment without artificial indoor lighting.

As described above, the installation of a blind-type light shelf system with more light shelf slats, allows light to be introduced more deeply into the indoor space. Furthermore, the low uniformity ratio of illuminance on the window and interior sides of light shelves, obtained in previous studies, was improved by reducing the illuminance with blind slats to provide a high uniformity ratio of illuminance at any setting angle. It is believed that the blind-type light shelf has high usability because it is separate from the design of the building envelope and can be used in combination with a curtain box, and it also has a low cost and is easy to install.

This study was conducted to improve the uniformity ratio of illuminance through a blind-type light shelf system. In the future, follow-up research on changes in the average illuminance and uniformity ratio of illuminance according to the angle and height of a blind-type light shelf will be performed.

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