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SIMULATION WORKS ON INTERIOR ILLUMINATION WITH NATURAL DAYLIGHT

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ABSTRACT
Solar light is a safe and clean energy. The use of natural light in office buildings is an effective way of energy saving. At present, the amount of electricity consumed by the lighting system occupies about 20%~30% of the total electricity consumption especially in office buildings in Japan [1]. Therefore, it is obvious that using daylight in the office space for illumination will be a great innovation. However, natural light source has variability and is difficult to control. In this research, we have proposed a method of attaching multiple blind reflectors to windows that can reflect light from the window to the ceiling, and then the diffused light from the ceiling is used for room lighting. In order to evaluate the energy saving amount when using such a lighting system on bright shining days, office lighting environment with various conditions throughout the whole year was simulated by using the daylighting system of our self-made simulator.

KEYWORDS: simulation, blind reflector, office, daylight.

I. INTRODUCTION
In recent years, the use of daylight has been recommended for the purpose of reducing lighting power consumption in offices, and daylight devices that actively use direct sunlight are being actively developed [2~7]. However, it is not easy to control the natural light entering the room due to the variability of solar altitude angle and solar azimuth angle according to different seasons. For example, on a sunny day, the sun altitude angle changes in accordance with time, therefore the intensity of incident sunlight from the window and the direction of incidence also change [8]. Furthermore, sunlight on a sunny day is too dazzling, thus it is often not used in working environment. Despite the existence of these problems, there is a little development of a lighting device that responds to the movement of the sun at present.

In order to solve this problem, when developing a window system for daylighting with light shielding which is effective against all seasons, lighting device that can be controlled according to the movement of the sun must be considered. For this reason, we have proposed a window lighting system equipped with blind reflectors whose angle can be controlled. This daylighting system works by having its reflectors that are attached to the window reflect incident sunlight to the ceiling and use the diffuse reflected light due to the coarse ceiling for room lighting. In this way, almost all light can be directed into the room and since diffused light from the ceiling is utilized, it can be expected that the degree of uniformity will be high in this process. Besides that, since many blinds are used, there is little influence on the work surface, and convenience in using this system is high. Also, it is possible to secure a large daylighting rate even when solar altitude changes constantly because angle change of blinds is possible.

However, when the slat angle changes naturally with the movement of the sun, then the illuminance distribution in the room also changes. Therefore, in this research, in order to enhance the lighting environment in the room, it is necessary to obtain the illuminance distribution according to the illuminance standard of JIS (Japanese Industrial Standard), and adjustment of the slat angle is important for this type of illumination system. Moreover, it is necessary to obtain not only the illuminance distribution but also the degree of uniformity (minimum illuminance / average illuminance) that satisfies the JIS conditions. Especially it is necessary to obtain the illuminance distribution and the uniformity of the room due to the change in the slat angle on fine weather. If these conditions are obtained, it can be considered to be a big step toward the field of using daylight as interior illumination. At

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the same time, energy saving can be achieved, more comfortable lighting environment can be expected, and sunlight is also good for human body.

In order to investigate the lighting environment, it is necessary to obtain the illuminance distribution of the work surface. To obtain the illuminance distribution, it costs a lot and takes a long time to design by performing actual measurements and manual calculations. Therefore, for reducing the time and expense required for the actual measurement of illuminance and manual calculations, a distribution simulation software which can be able to calculate the illuminance using daylight is preferable. We developed such a simulator implementing the Monte Carlo ray tracing method with Visual C# in our previous research works [9, 10]. It was shown that on cloudy days, using daylight from the window for illumination can save power consumption by 33% or more comparing to using artificial illumination tools [10]. We also confirmed that the illuminance distribution inside the room greatly changes depending on the presence or absence of the blind reflectors used for the window [9].

In this research, this illumination distribution simulation software was used for the construction of lighting environment in the indoor space using daylight in the case of a sunny fine day. The indoor illumination distribution when the angle of incident light from the window and the angle of the blinds attached on the window throughout the whole year was simulated and evaluated. From the obtained results, it is found that the constructed system can be used for indoor lighting by daylighting through the window, and it can be expected to dramatically reduce power consumption by using daylight as an auxiliary role for lighting.

II. SIMULATION PREPARATION

Lighting Standards

The lighting standard of this research is over 500 lx for the illuminance on the indoor work surface in accordance with the 「Lighting Standard JIS Z 9110: 2010」 of the Japanese Industrial Standard (JIS). The illuminance

Table 1. Lighting Standard (Office)

illuminance[lx]	500~
uniformity	0.7~1

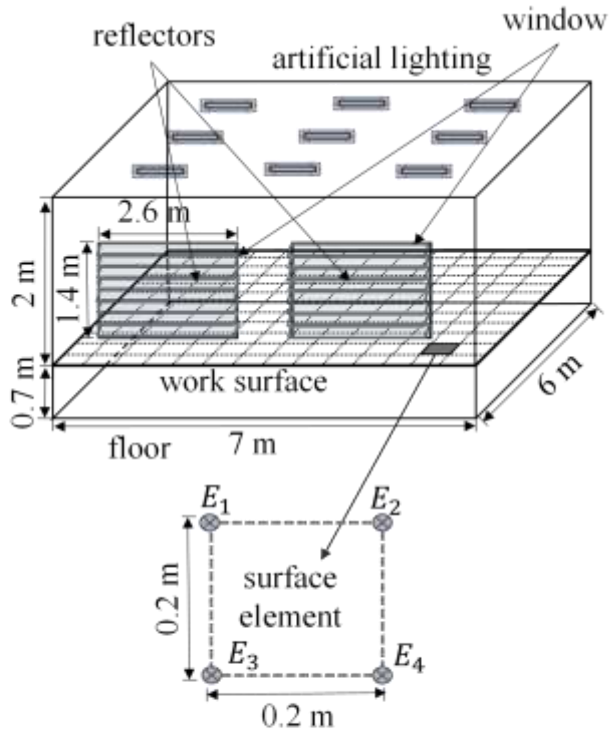

Fig. 1. Model diagram for the simulation

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criterion is satisfied when the uniformity (minimum illuminance / average illuminance) is 0.7 or more in the range of more than 1 m from the wall surface [11] (Table 1).

Simulation Model

Fig. 1 shows the outline of the model space used for this simulation works. The model space is assumed to be an office space, and simulation was conducted using a work surface of 0.7 m above the floor. The reflectance of each surface was 80% for the ceiling surface, 70% for the wall surface and 40% for the work surface [12, 13]. On one of the wall surfaces, two windows of 2.6 m × 1.4 m were installed at the same height as shown in Fig. 1. And windows were faced to south. In this study, the number of calculation set per window was 50 million to achieve an optimum accuracy of illuminance distribution.

In the simulation, 9 light fixtures were installed on the ceiling surface of the model space as shown in Fig. 1. The installed luminaire was Hitachi HNM 4205 V fluorescent lamps actually used in general offices as well as the writers' working laboratory. Total luminous flux was 7400 lm, instrument efficiency was 90.2%, and power consumption was 64 W [14]. In addition, the number of calculations per lighting fixture was 20 million cycles in order to achieve the best accuracy illumination distribution and calculation time. Again, the surface element was 0.2 m × 0.2 m in size, and the observation surface was divided into 1050 regions of 35 rows × 30 columns to obtain the illuminance by 4 points methods according to 「Illuminance Measurements for Lighting Installations JIS C 7612-1985」 shown in eq.(1) [15].

$$E = \frac{1}{4}\Sigma E_i = \frac{1}{4}(E_1 + E_2 + E_3 + E_4) \tag{1}$$

In this research, since the light source enters the room with dazzling sunlight from the window, it is necessary to attach blind-shaped reflectors to the window. Total sunlight entering through the window reflected to the ceiling through the reflectors is as shown in Fig. 2. Furthermore, in consideration of practicality, the number of blind

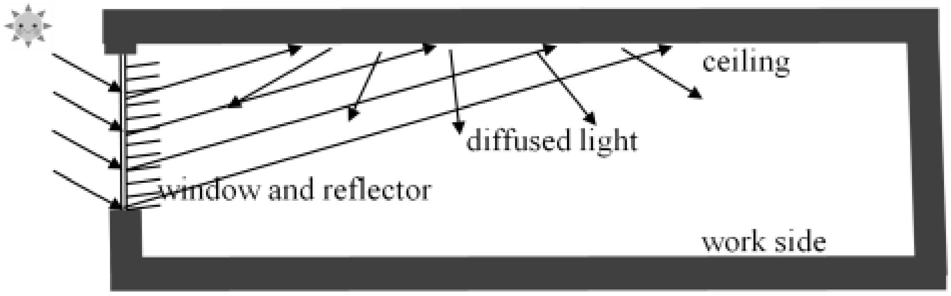

Fig. 2. Daylighting method by reflectors

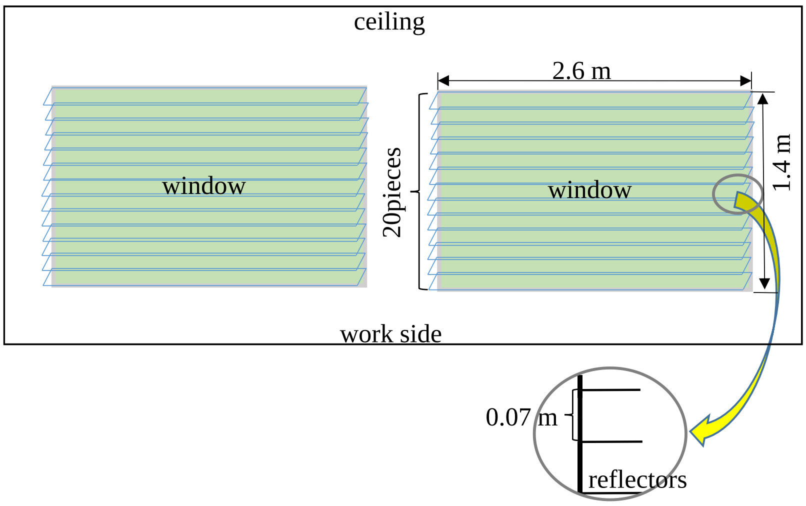

Fig. 3. Light reflector beside the window

reflection plates was set to 20 pieces as shown in Fig. 3, and the interval between the slats was set to 0.07 m. A specific explanation of the reflector will be described later.

Conditions for Sunlight

Since the earth revolves around 23.5° from the direction perpendicular with respect to the revolution plane, the azimuth of the sun changes throughout the cycle of 1 year [16]. The earth revolves the sun at almost the same place on the same day of every year. It means that summer and winter happens on almost the same day in each year for a fixed place. This concept also applies on the temperature which is high or low on roughly the same day of every year. For example, in the summer of Akita, the solar elevation angle is the highest at about 75° (around 12 o'clock) in height, and it is about 50° (around 12 o'clock) in the spring and autumn. The solar elevation angle in the winter becomes the lowest, which is about 30° (around 12 o'clock) [17]. Also, the azimuth of the sun changes with seasons and time.

The angle of sunlight used in this simulation is the sun angle at Akita University. The longitude of Akita University is 39.7° and the latitude is 140.1° [18]. Changes in solar elevation angle and solar azimuth angle which is based on the season and time zone of Akita University were calculated from this position information. In this research, daylight was used from 9 am to 3 pm in order to avoid problems such as glowing sunset [19~21]. The average solar elevation angle and solar azimuth angle used in the simulation are summarized in Table 2.

The amount of sunlight flux used in this study is based on actual measurement. The intensity of sunlight coming from the window not only relates to the time zone but also to the air humidity and the thickness of the cloud. Based on the measured results, it was found that the change in daylight illuminance is large not only on cloudy days but also on sunny days. In order to reduce variations in actual measurement values used for simulation, we used the average values. In addition, in order to prepare a simulator that can be used for all seasons, this research measured the average value of the illuminance on 10 clear days before and after the summer, the winter and the autumn day. Table 3 summarizes the averaged measured data.

Conditions on Reflector

The solar angle varies depending on the season and time zone. So it is obvious that the angle of light entering indoors from the window also changes, and thereby affecting the indoor lighting environment as well. The angle and the illumination environment may vary greatly depending on change in angle and type of the blind reflectors.

Table 2. Solar angle with time at Akita University

season / time	summer		winter		spring・autumn	
	altitude angle	azimuth angle	altitude angle	azimuth angle	altitude angle	azimuth angle
9:00～10:00	55°	110°	20°	150°	40°	130°
10:00～11:00	65°	130°	25°	160°	45°	150°
11:00～12:00	75°	170°	30°	180°	50°	170°
12:00～13:00	70°	230°	25°	190°	50°	200°
13:00～14:00	60°	240°	20°	210°	40°	220°
14:00～15:00	50°	260°	15°	220°	35°	230°

Table 3. Solar luminous flux through a window [lm]

season / time	summer	winter	spring・autumn
9:00～10:00	26151.8	69287.7	41826.0
10:00～11:00	38186.5	73352.5	63046.7
11:00～12:00	48025.9	75656.0	75198.0
12:00～13:00	42579.9	92249.0	71753.1
13:00～14:00	36777.2	86609.6	55768.0
14:00～15:00	15911.3	83251.7	50122.6

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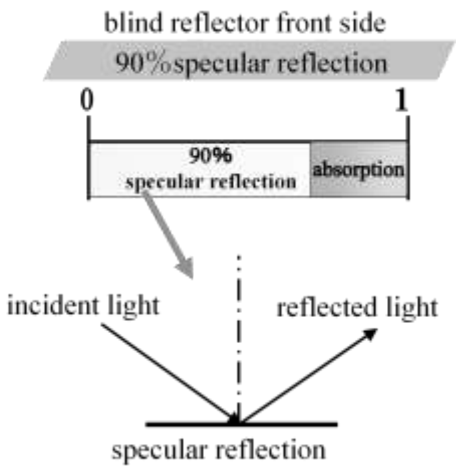
In order to reduce the power consumption of indoor lighting fixtures by daylighting from the window, it is necessary to know how the change in solar position affects the change of the indoor environment. To produce a comfortable lighting environment for all conditions, it is necessary to consider the width of the blind reflector and the slat angle. As part of this preparation, the width of the blind reflector and the slat angle is obtained by calculation in order to confirm the characteristics of the material of the reflector.

- Material of Reflector

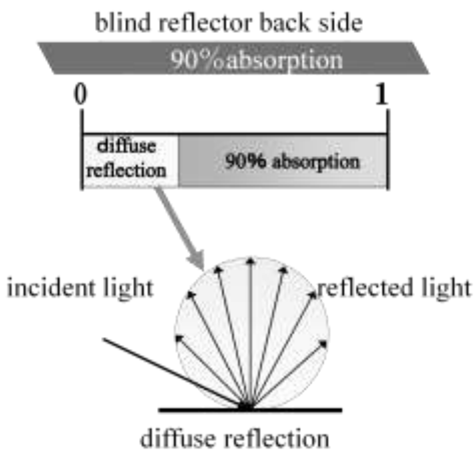
For the reflective materials, it is necessary to reflect light and maintain high performance under high temperature and high luminous flux, thereby making it possible to utilize a high utilization ratio of sunlight. Many companies are currently developing and producing this optical reflective silicone material [22]. By referring to those product characteristics, the front of the reflector for this simulation is set as a mirror, and the incident daylight is reflected to the ceiling with 90% specular reflection and the remaining light is absorbed [23]. 90% of the light is absorbed on the back surface of the blind reflector, and the remaining light is set as diffuse reflection (Fig. 4).

- Reflector Angle

As described in Fig. 2, incident daylight is taken into the room by a lighting system using blind reflectors whereby its type and angle can be changed. In this research, in order to improve the performance and practicality of the



(a) Front side



(b) Back side

Fig. 4. Determination of reflection and absorption

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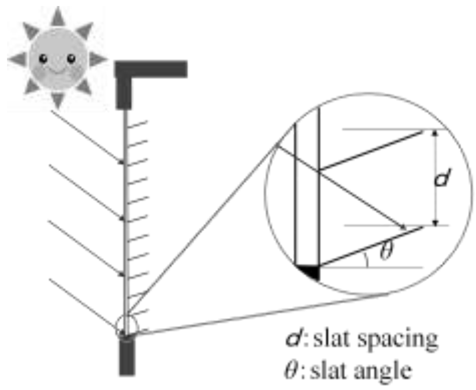
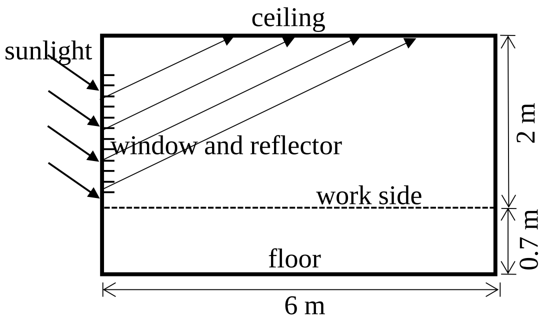
system, incident light was reflected on the ceiling as much as possible. For this reason, the angle of the blind reflector was determined.

As shown in Fig. 5 (a), the reflectors were controlled by changing the angle about the innermost side of the reflector. The angle of the reflection plate was 0° when it is perpendicular to the window, positive when turned upwards, and negative when turned downwards. In order to create a comfortable lighting environment in the room, incident sunlight could be reflected to the center of the ceiling as shown in Fig. 5 (b). At that time, the angle of



(a) Determination of reflector angle



(b) Reflected light path of reflector's angle

Fig. 5. Lighting from the window

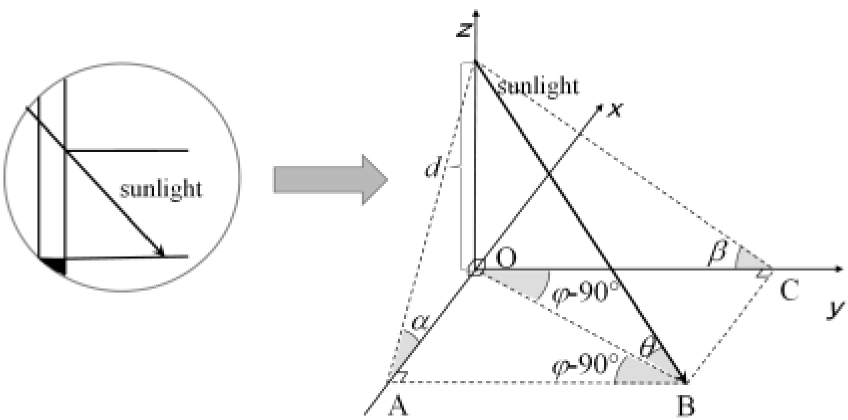


Fig. 6. Geometric relationship between sun angle and reflectors

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Table 4. Angle of the reflectors

time \ season	summer	winter	spring・autumn
	a_{MID}	a_{MID}	a_{MID}
9:00～10:00	-29.1°	-2.2°	-17.1°
10:00～11:00	-27.4°	-4.0°	-15.3°
11:00～12:00	-28.4°	-5.8°	-16.0°
12:00～13:00	-29.2°	-3.5°	-16.7°
13:00～14:00	-27.7°	-2.2°	-17.0°
14:00～15:00	-31.6°	-0.4°	-14.5°

the blind reflector was a_{MID}. For a known size of room, if the angle of incidence sunlight to the reflector wasα, the angle a_{MID} of the reflector could be obtained by the following equations.

$$a_{\mathrm{MID}} = \frac{tan^{-1}\frac{1}{3} - \alpha}{2} \ [°] \tag{2}$$

As shown in the bottom left part of Fig. 6, sunlight can enter through the gap of the reflectors and is reflected on the reflectors. For a right 3D coordinate system,

θ : Solar elevation angle
φ : Solar azimuth angle
$\uparrow$: Sunlight
α : Projection of x-axis of the sun angle
β : Projection of y-axis of sun angle
a : Rotation angle of reflector
d : Spacing between reflectors

In this coordinate system, the distance between the reflectors was 0.07 m, and the sun angle was obtained from Table 2. Thus, OB was obtained by the following equation.

$$\mathrm{OB} = \frac{d}{tan\theta} \ [\mathrm{m}] \tag{3}$$

OA could also be obtained from equation (4)

$$\mathrm{OA} = \mathrm{OB} \times \sin(\varphi\text{-}90°) = \frac{d \times \sin(\varphi - 90°)}{tan\theta} \ [\mathrm{m}] \tag{4}$$

Also, α and OA had the following relationship.

$$\tan\alpha = \frac{d}{OA} \tag{5}$$

From simultaneous equations (4) and (5), projection α of the sun angle x-axis could be obtained by equation (6).

$$\alpha = tan^{-1}\frac{tan\theta}{\sin(\varphi - 90°)} \ [°] \tag{6}$$

By substituting equation (6) into equation (2), angles a_{MIN} of the reflector were obtained and summarized in Table 4. Here, the values of θ and φ were the same values as shown in Table 2.

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- Width of Reflector

Determining the illuminance inside of a room, one has to take account of the angles of the blind reflectors and the width of the reflectors. In determining the width of the blind reflector plate, reflection of the incident light in the indoor environment, incident daylight reflected by blind must not affect the other blinds. Therefore, it was considered that there was a limit value for the width of the blind, and its limit value could be obtained from the geometrical relationship between solar evolution angle and blind.

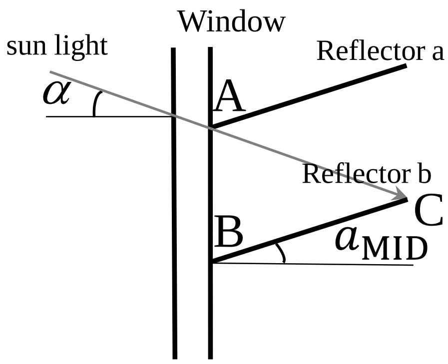

Fig. 7. Side view of a reflector's structure

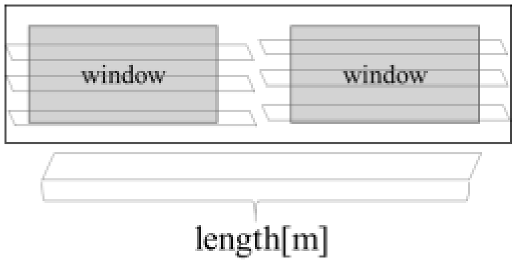

Fig. 8. Setting of reflectors (length)

Table 5. Minimum width[m] of reflectors

season / time	summer	winter	spring・autumn
9:00～10:00	0.0221	0.1833	0.0733
10:00～11:00	0.0280	0.1645	0.0824
11:00～12:00	0.0245	0.1478	0.0789
12:00～13:00	0.0216	0.1697	0.0754
13:00～14:00	0.0269	0.1833	0.0733
14:00～15:00	0.0132	0.2045	0.0871

Table 6. The shortest length[m] of the reflector

season / time	summer	winter	spring・autumn
9:00～10:00	2.69	2.79	2.73
10:00～11:00	2.65	2.70	2.67
11:00～12:00	2.61	2.60	2.62
12:00～13:00	2.64	2.65	2.64
13:00～14:00	2.67	2.79	2.69
14:00～15:00	2.72	2.94	2.75

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Considering a daylighting system with a blind reflector attached as shown in Fig. 7, α was obtained from equation (6) by the projection of the x-axis of the sun angle. At that time, the sunlight passed through the gap between the reflecting plates a and b. For a light beam m, which was reflected at the point C of a reflector b and reached the ceiling, the minimum limit value of the blind width was the length of the side BC. When the width became shorter than the length of the side BC, dazzling daylight passed through the gap of the reflector plate and illuminated the workplace directly. Therefore, in this section we examined the width of the blind reflectors.

In order to obtain the limit length of the blind reflectors' width in ΔABC as shown in Fig. 7, the BC side was the shortest length of the reflector, and from the conditional equations (7), (8), (9), BC was obtained by the sine theorem as shown in equation (10) . Here a_{MID} was the angle of the blind reflector and α is the projection of the x axis of the sun angle. The data about the limit of the reflector width was summarized in Table 5.

$$\angle BAC = 90° - \alpha \tag{7}$$

$$\angle ABC = 90° - a_{\mathrm{MID}} \tag{8}$$

$$AB = 0.07 \text{ [m]} \tag{9}$$

$$BC = \frac{AB \times \sin(\angle BAC)}{\sin(180° - \angle BAC - \angle ABC)} = \frac{\tan\theta}{\sin(\varphi - 90°)} \text{ [m]} \tag{10}$$

From Table 5, it can be seen that when the width of the reflector is set to 10 cm, its practicality is improved and can be applied to most time zones of the spring, summer and autumn. In the winter, based on the data in Table 5, the amount of daylight incident from the window of winter is larger than the other seasons. Enough lighting is obtained even if the sunlight is partially blocked, thus the width of the reflector in the winter is set to 20 cm.

- Length of reflector

In the case of fine days, sunlight in the morning and evening is oblique and illuminates reflectors. If the length of the reflector is set to be the same as the window's length, dazzling sunlight entering the window at an oblique angle will illuminate the work surface through the gap between the reflectors. To avoid this, the length of the reflector used in this research is set to be longer than the length of the window as shown in Fig. 8. Here, the shortest length of the reflector in the 3D coordinate system of Fig. 6 was calculated by the formula (11). The values were summarized in Table 6.

$$OC = OB \times \cos(\varphi\text{-}90°) = \frac{d \times \cos(\varphi\text{-}90°)}{\tan\theta} \text{ [m]} \tag{11}$$

Looking at the results in Table 6, the length of the reflector is required to be 2.75 m or longer in the summer, spring and autumn so that all the incident light is reflected to the ceiling, and in the winter it is necessary for the length to be more than 2.94 m. Based on the results, the length of the reflector is set to 2.75 m in the summer, spring and autumn, and 2.95 m in the winter.

- Setting of reflector condition

Based on the above calculations, the dimensions of the reflector were set as shown below during the actual simulation works.

- Number of reflector plates: 20 (each window)
- Spacing between reflectors: 0.07 m
- Reflector plate length: 2.75 m in summer, spring, autumn, 2.95 m in winter.
- Width of reflector: 0.1 m in summer, spring, autumn, 0.2 m in winter.
- Reflector angle: a_{MID} (See Table 4.)

III. RESULTS AND DISCUSSION

Evaluation of using of natural light in all seasons

In the office model space shown in Fig. 1, the angle of reflectors that was attached to the front of the window is a_{MID} and it changes according to the change in the solar angle and reflect incident sunlight to the ceiling. As a

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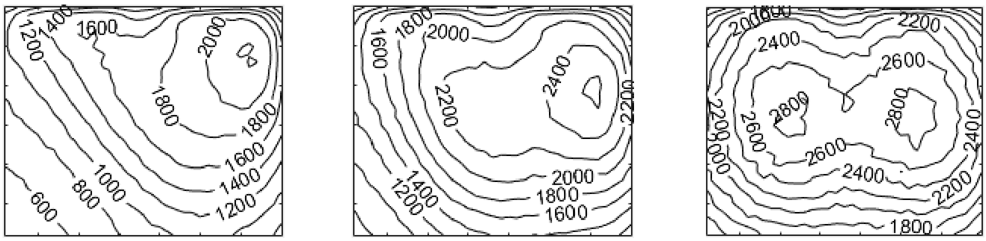

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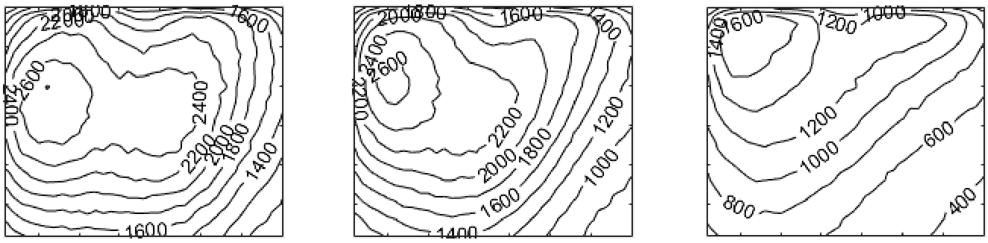
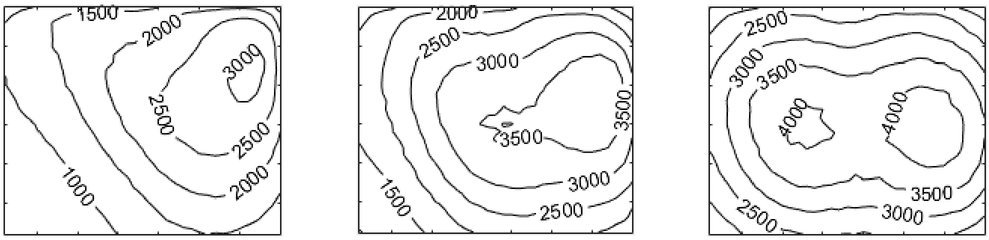


(d) 12:00～13:00 (e) 13:00～14:00 (f) 14:00～15:00

Fig. 9. Illuminance distribution for summer



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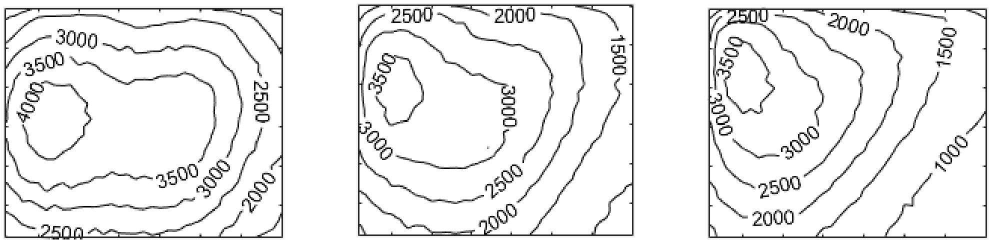
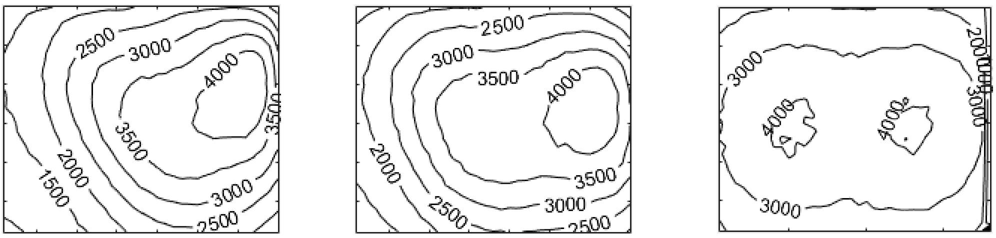
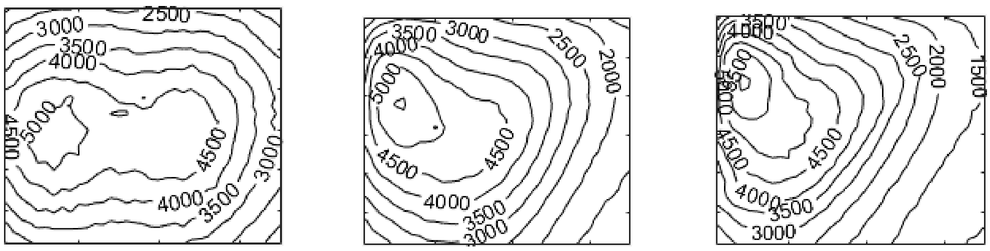


(d) 12:00～13:00 (e) 13:00～14:00 (f) 14:00～15:00

Fig. 10. Illuminance distribution for spring ・autumn



(a) 9:00～10:00 (b) 10:00～11:00 (c) 11:00～12:00



(d) 12:00～13:00 (e) 13:00～14:00 (f) 14:00～15:00

Fig. 11. Illuminance distribution for winter

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Table 7. Simulation results for summer

results / time zone	maximum illuminance [lx]	minimum illuminance [lx]	average illuminance [lx]	uniformity
9:00～10:00	2214.3	644.2	1556.2	0.41
10:00～11:00	2627.4	1118.1	2127.6	0.53
11:00～12:00	2916.6	2084.1	2591.1	0.80
12:00～13:00	2811.9	1357.6	2337.8	0.58
13:00～14:00	2686.1	932.6	2040.7	0.46
14:00～15:00	1728.6	431.6	1099.4	0.39

Table 8. Simulation results for spring ・autumn

results / time zone	maximum illuminance [lx]	minimum illuminance [lx]	average illuminance [lx]	uniformity
9:00～10:00	3127.0	797.1	2061.5	0.39
10:00～11:00	3970.4	1642.5	3072.7	0.53
11:00～12:00	4284.4	2730.6	3646.6	0.75
12:00～13:00	4376.0	2320.3	3489.2	0.67
13:00～14:00	3705.2	1218.1	2722.1	0.45
14:00～15:00	3769.5	853.1	2350.9	0.36

Table 9. Simulation results for winter

results / time zone	maximum illuminance [lx]	minimum illuminance [lx]	average illuminance [lx]	uniformity
9:00～10:00	4403.7	1402.4	3172.6	0.44
10:00～11:00	4426.1	1936.7	3425.1	0.57
11:00～12:00	4182.6	2634.9	3566.8	0.74
12:00～13:00	5278.3	2795.8	4275.9	0.65
13:00～14:00	5541.2	1731.6	3899.2	0.44
14:00～15:00	5929.7	1294.2	3616.9	0.36

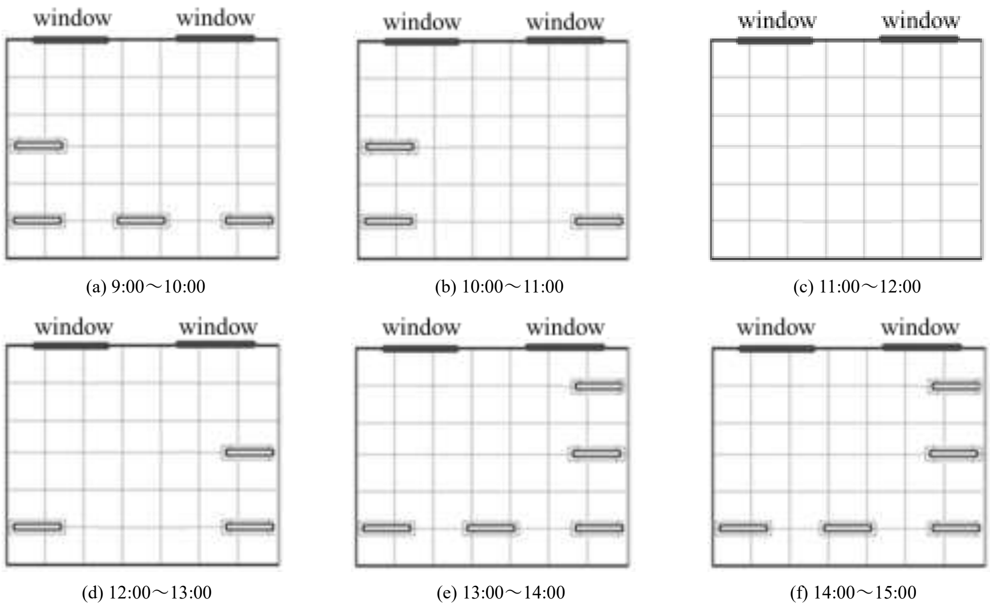

Fig. 12. Lighting fixture placement pattern for summer

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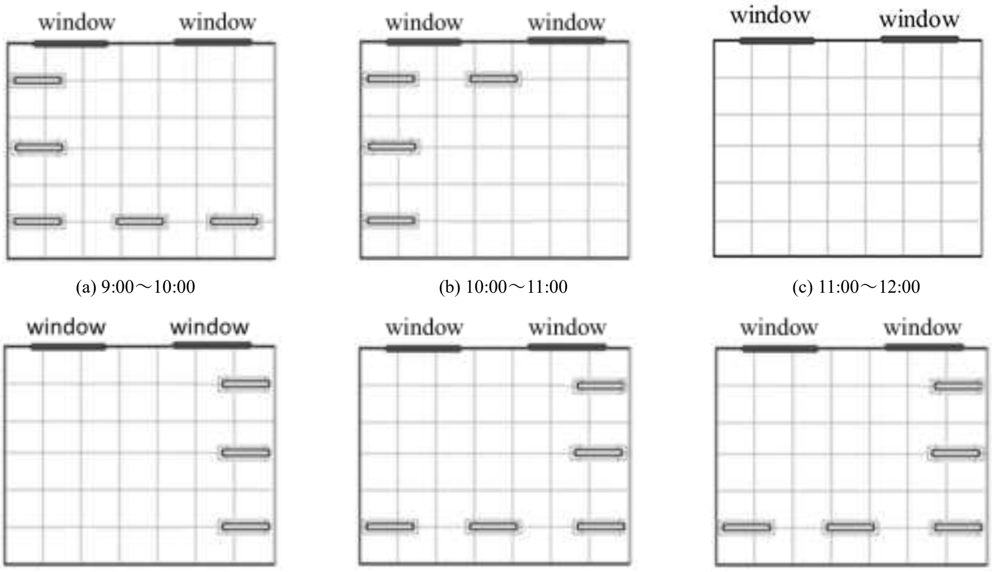
result, we examined the change in the illuminance of the observation surface. In this research, we evaluated illuminance distribution of all 4 seasons. And we evaluated the results of spring and autumn under the same situation because sun orbits at almost the same location in spring and autumn. The simulated illuminance distribution for a year is shown in Fig. 9 ~ Fig. 11.

Looking at the illuminance distribution charts in Fig. 9 ~ Fig. 11, the center of the light entering the room moved from the west to the east (from the right to left) as time changed from 9:00 to 15:00. It was also observed that the best lighting was between 11:00 and 12:00 in every season. The natural light at this time seems to be the brightest. To make a more detailed comparison, the numerical results were summarized in Table 7 ~ 9.

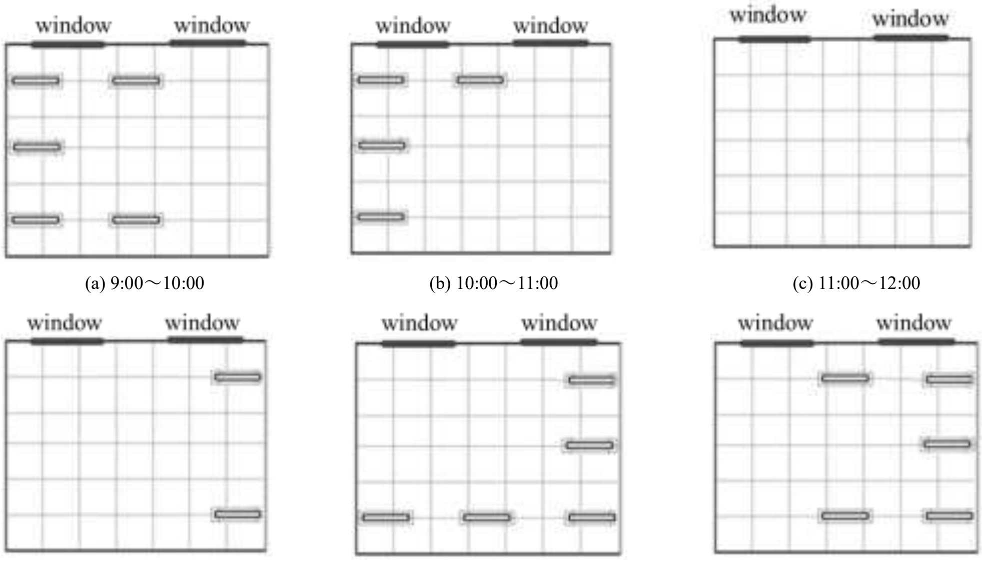
The result of illuminance in Table 7 ~ 9, the maximum illuminance, the minimum illuminance, and the average illuminance gradually became brighter from 9:00 and peaked at the time zone from 11:00 to 13:00, and after 12:00 it reduced gradually for all seasons. But in winter, the maximum illuminance tended to rise between 11:00 and 15:00. We believe that this happened as the light striking a part of the east (left) wall, and the illuminance around



(a) 9:00～10:00 (b) 10:00～11:00 (c) 11:00～12:00

(d) 12:00～13:00 (e) 13:00～14:00 (f) 14:00～15:00

Fig. 13. Lighting fixture placement pattern for spring ・autumn



(a) 9:00～10:00 (b) 10:00～11:00 (c) 11:00～12:00

(d) 12:00～13:00 (e) 13:00～14:00 (f) 14:00～15:00

Fig. 14. Lighting fixture placement pattern for winter

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that area got brighter. The direction of the sun relative to the window became diagonal gradually after 12:00 causing the dazzling sunlight to concentrate near the wall with time. Moreover, the illuminance for almost all time zones was above 500 lx, which satisfied the illuminance standard. But the minimum illuminance was lower than 500 lx between 14:00 and 15:00 in summer. Therefore, it was necessary to lighten up the room. Looking at the result of the uniformity, the ratio of uniformity rose steadily from 9:00, similar to the result obtained for illuminance. The uniformity peaked in the time zone from 11:00 to 12:00, and gradually lowered after 12:00. Referring the numerical values, the ratio of uniformity for the time periods other than 11: 00 to 12: 00 was less than 0.7. In order to satisfy the illuminance criterion, it is necessary to increase the ratio of uniformity of the work surface by adjusting the lighting conditions.

In order to use appropriate light, with reference to the illuminance distribution chart shown in Fig. 9 ~ 11, a light source was attached from a place with low lighting and various lighting fixture arrangement patterns were simulated. The best result of each time zone and the lighting fixture placement pattern at that time are shown separately in Fig. 12 ~ 14. And in order to investigate whether illuminance standard was satisfied, the data were summarized in Table 10~ 12.

Since the minimum illuminance of all time periods exceed 500 lx, the illuminance data of Table 10 ~ 12 meet the illumination standard. When looking at the data on the ratio of uniformity, all the time periods within the lighting time period are more than 0.7 in summer. In spring/autumn, the uniformity in the time zone from 10:00 to 13:00 was above 0.7, satisfying the illumination standard. In winter, most of the time periods within the lighting time were above 0.7 satisfying the illuminance standard. The uniformity of other time zones was less than 0.7 and

Table 10. Simulation results for summer

results / time zone	maximum illuminance[lx]	minimum illuminance[lx]	average illuminance[lx]	uniformity
9:00～10:00	2423.7	1672.8	2110.1	0.79
10:00～11:00	2853.1	2074.8	2532.8	0.82
11:00～12:00	2916.6	2084.1	2591.1	0.80
12:00～13:00	3069.4	2248.3	2742.8	0.82
13:00～14:00	3021.9	2137.9	2745.8	0.78
14:00～15:00	2151.5	1630.5	1804.5	0.90

Table 11. Simulation results for spring ・autumn

results / time zone	maximum illuminance[lx]	minimum illuminance[lx]	average illuminance[lx]	uniformity
9:00～10:00	3443.0	2001.7	2766.8	0.72
10:00～11:00	4203.3	2686.4	3702.7	0.73
11:00～12:00	4284.4	2730.6	3646.6	0.75
12:00～13:00	4585.7	3020.0	3931.3	0.77
13:00～14:00	4042.3	2428.0	3427.1	0.71
14:00～15:00	4066.0	2064.8	3055.9	0.68

Table 12. Simulation results for winter

results / time zone	maximum illuminance[lx]	minimum illuminance[lx]	average illuminance[lx]	uniformity
9:00～10:00	4718.6	2599.5	3951.5	0.66
10:00～11:00	4650.5	2980.7	4055.1	0.74
11:00～12:00	4182.6	2634.9	3566.8	0.74
12:00～13:00	5370.5	3312.3	4541.6	0.73
13:00～14:00	5852.6	2938.9	4677.8	0.63
14:00～15:00	6244.4	2501.5	4395.5	0.57

Table 13. Percentage of energy saving using natural light

season / time zone	summer		spring and autumn		winter	
	number of lights	energy saving	number of lights	energy saving	number of lights	energy saving
9:00～10:00	4 lights	55.6%	5 lights	55.6%		
10:00～11:00	3 lights	66.7%	4 lights	55.6%	4 lights	55.6%
11:00～12:00	0 light	100%	0 light	100%	0 light	100%
12:00～13:00	3 lights	66.7%	3 lights	66.7%	2 lights	77.8%
13:00～14:00	5 lights	44.4%	5 lights	44.4%		
14:00～15:00	5 lights	44.4%				

Table 14. Percentage of energy saving (all day)

season / time zone	summer		spring and autumn		winter	
	power consumption [W]	energy saving	power consumption [W]	energy saving	power consumption [W]	energy saving
9:00～18:00	3008	42.0%	3392	34.6%	3840	25.9%

could not be used. This might happen due to the dazzling sunlight reflected from the ceiling onto the left and right walls in the morning and afternoon to the left and right walls. Dazzling lights on the left and right walls reflected onto each other, causing the illuminance to increase and uniformity to decrease. Tis problem can be solved by adjusting the amount of light taken from the window, adjusting the size of the reflectors or blocking a part of the incident light. Based on the results above, the time period during which daylighting may be possible around 9:00~14:00 in summer, 10:00~13:00 in spring/autumn, and 10:00~13:00 in winter.

Consideration of Power Consumption

If the blind-shaped reflector attached to the window can be controlled as shown in Fig. 2, the combination of artificial lighting and daylighting from the window is effective for energy conservation [10]. Here, we have calculated how much energy can be saved for each time zone for lighting system. When no sunlight enters from the window, 9 lights are arranged evenly on the ceiling (Fig.). In other words, it is the lighting environment of a typical office at night. Table 13 shows the amount of energy saved for each time zone. Here, the number of lights is 9 (night office environment) for boxes with diagonal lines.

Based on the data in Table 13, in the case of combination of artificial lighting and daylighting from the window, the number of lighting fixtures installed was the smallest for all seasons, and power could be saved most from 11:00 to 12:00, and it was found that illumination standard is satisfied even if it is not light up at this time. The power consumption at this time was compared with the power consumption when the amount of lighting fixtures was 9 lights, and it was found that 100% of power consumption could be reduced.

In the actual office rooms (i.e. our working laboratory), the curtains are usually drawn as sunlight is too dazzling, therefore 9 lights are usually used from morning till evening. In the same time zone, it is possible to save energy by 55.5% in the morning and save at least 44.4% in the evening. Also, the power consumption during the day was calculated and summarized in Table 14 by assuming the working hours in the office rooms for a day are from 9:00 to 18:00 in accordance with Japanese working hours at office. In this example, as described in section 2, the power consumption per hour was 64 W. Therefore, the power consumption during a general day is 64 W × 9 fluorescent lamps × 9 hours = 5184 W. Compared with the daytime power consumption when combining artificial lighting and lighting from the window, the energy conservation rate was calculated and summarized in the Table 14.

Based on the data in Table 14, by attaching the blind-shaped reflector to the window and controlling the natural light entering a room, we would be able to reduce power consumption by 42% in the summer, 34.6% in the spring and autumn, and 25.9% in the winter while using a lighting system combining artificial lighting and natural daylight through a window compared to using artificial lighting system only. Therefore it can be said that using daylight from the window is very effective in reducing power consumption for lighting in office rooms.

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IV. CONCLUSION

In this research, we proposed a method to utilize diffused light from the ceiling by using blind reflectors which changed their reflection angle freely. We have discussed about the possibilities of using direct daylight for interior illumination with various simulations in all seasons by using this illumination system. As a result, in the same time zone, daylighting can save energy by 55.5% during morning and save at least 44.4% in the afternoon. And it can reduce power consumption for more than 25.9% in office per day by using a lighting system that combines artificial lighting and daylighting through a window. But the maximum illuminance is slightly higher for winter, and we believe that this problem can be solved by adjusting the amount of light taken from the window, adjusting the size of the reflector, or blocking a part of the incident light. Based on the above results, it can be said that daylighting from window is effective in reducing power consumption.

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