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Grid Lighting System for Energy Saving Through Gradation Illuminance Control that Responds Inflow of Natural Light

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Abstract.

Background: In the indoor space where natural light inflows into, energy consumption can be saved by controlling indoor lighting together with illuminance by natural light. However, there are few studies on energy saving in the lighting environment where architectural lightings like luminous ceiling or multiple lightings are applied.

Methods/Statistical analysis: This paper proposes a grid lighting system that realizes lighting energy saving through a gradation illuminance technology in response to natural light which is kept on changing every moment and inflows into windows. Therefore, a gradation lighting was implemented by installing M x N LED lightings that could be controlled individually on the indoor ceiling and blinds that adjusted amount of natural light inflow. Illuminance at each zone of the indoor space was measured and an adequate illuminance was provided per each zone in response to the gradual difference of illuminance occurring at each zone according to the inflow status of natural light that changed over time.

Findings: 30 LED lightings were installed on the ceiling in the proposed grid lighting system and illuminance sensors were arranged in the equally divided four zones on the floor. The average illuminance and uniformity of indoor light environment according to inflow of natural light were measured. After comparing differences between the average illuminance and indoor recommended illuminance, a gradation illuminance technology was developed in such way that if the average illuminance was low, the illuminance was increased stepwise starting from the darkest indoor zone, while, if the indoor recommended illuminance was higher than the average, it was to lower the illuminance from the brightest zone of indoor. The recommended illuminance during the experiment was set to 300-600 lux, the color temperature to 5400 K, and uniformity to 0.3. It was confirmed that the proposed system maintained the indoor light environment adaptively by controlling the blinds at 10 min. interval and grid lighting at 30 seconds interval even the solar angles and weather were changed.

Improvements/Applications: The comparison of general lighting environment from sunrise till sunset by selecting one bright day and one cloudy day showed that the proposed lighting system saved power consumption on an average 23% than conventional lighting environment while maintaining recommended illuminance and uniformity (higher than 0.3) for all hours of the day.

Keywords: Grid Lighting, Energy Saving, Gradation, Illuminance Control, Natural Light.

1. INTRODUCTION

Conventionally, most of the indoor lightings simply provided light by constructed with luminaires that provided a fixed illuminance[1]. Recently, as LED light sources, luminaires, and IoT technology developed, lighting technologies focusing functions such as construction of an adequate light environment according to the activities or purposes of occupants, or realization of energy saving have been introduced[2, 3]. Particularly, since lighting energy accounts for about 20% of total energy consumption in building, efforts to save energy by the introduction of LED lightings that could control illuminance have been continued[4]. Futagami Takuya et al. proposed a gradation control method that could control several luminaires arranged in indoor simulating presence of occupants and inflow of natural light [5]. In addition, architectural lighting technologies such as luminous ceilings where lightings were arranged in most of the ceiling surface to decrease UGR and to increase uniformity have been introduced[6, 7]. Luminous ceiling is an architectural lighting technology that arranges lighting devices or lighting sources on most of the indoor ceiling and it decreases UGR and improves uniformity of indoor light environment, thus is applied in a variety of spaces like hotel lobbies and office areas [7]. Other methods employ several luminaires or large-scale light sources in indoor (ceiling) to make glare-free lighting or to improve light quality like providing uniformity of light[8]. Nonetheless, such luminous ceiling or multi-lightings would be disadvantageous in terms of energy saving. Furthermore, just like general lighting environment, if a fixed illuminance is provided not in response to changes in indoor illuminance caused by inflow of natural light, unnecessary lighting energy loss would incur [9,10].

This paper proposes a grid lighting system that saves energy by the realization of LED lighting control in response to changes of indoor light environment caused by inflow of natural light for which LED lighting facility is constructed in a broad area of ceiling surface, for example, a luminous ceiling. Therefore, LED lamps of M x N structure were installed with a constant gap on the ceiling surface. The inflow amount of natural light was adjusted by fixing Venetian Blinds whose angle could be adjusted. The illuminance sensors were also installed at each point in the indoor to analyze illuminance changes and then blinds and each LED lighting were controlled based on the measured results. The energy saving lighting control that provided required illuminance to maintain indoor recommended illuminance (300-600 lux, as per KS A 3011) at each zone in indoor was executed. The comparison experiment between general lighting and proposed lighting was performed to check lighting energy saving.

2. GRID LIGHTING SYSTEM FOR SAVING LIGHTING ENERGY

In this paper, a lighting system is proposed for energy saving in the grid lighting environment installed with multiple LEDs in a broad area on the ceiling surface. The proposed system proved to control illuminance of individual LED in response to inflow of natural light which changed continuously over time in a day. Figure 1 is the schematic diagram of the proposed lighting system.

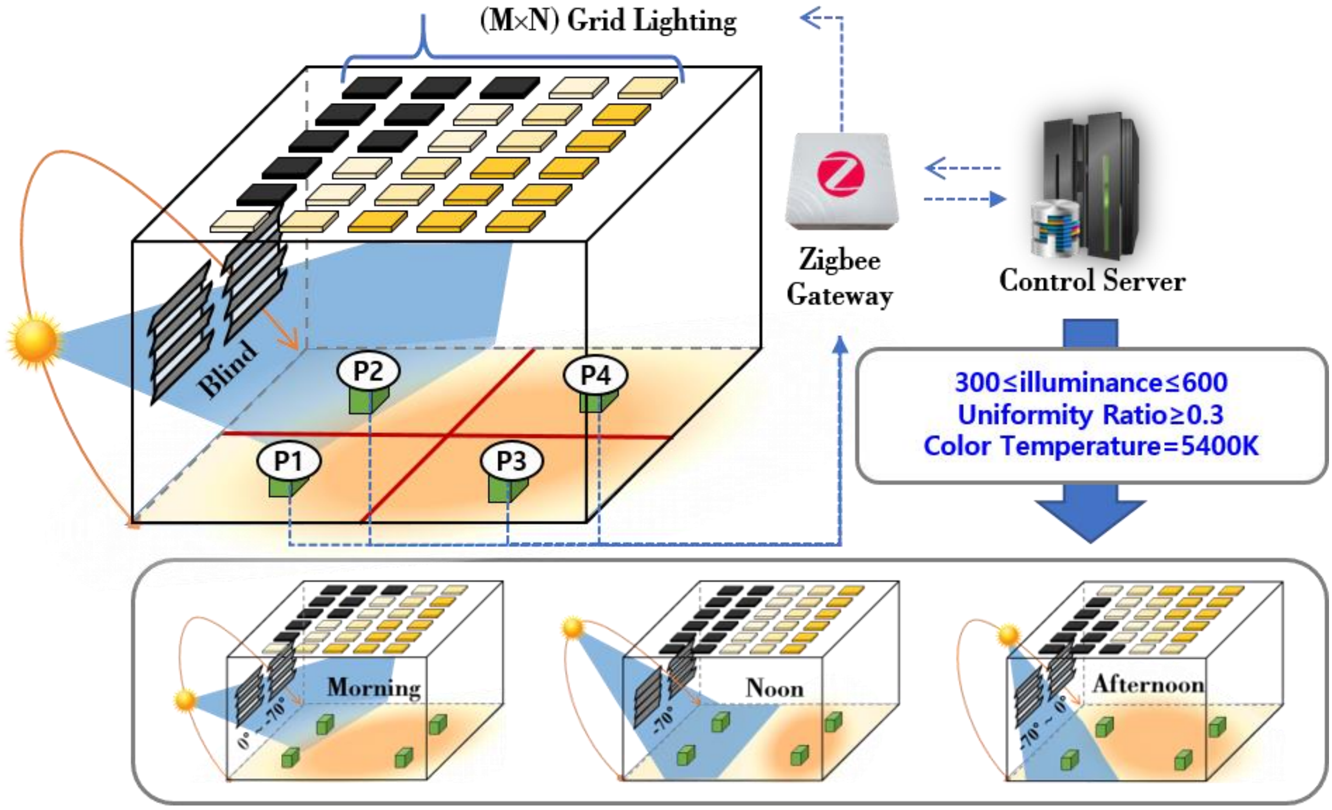


Figure 1. Schematic diagram of grid lighting system

The grid lighting system in Figure 1 was realized by installing M x N (line x row) LED general lightings which could be controlled individually. In addition, blinds that could control inflow of natural light were installed on the walls. The area was divided into left and right from the window and again into window side and inner side (wall surface) to make a total of four control zones. Illuminance sensors were installed in each zone to measure illuminance of each zone. Along with the illuminance sensors, a control server, a Zigbee based gateway which supported wireless communication between each device, and a smart plug to measure lighting energy usage were also installed. The proposed lighting system measured illuminances of lighting environment constructed in each indoor zone created by the inflow of natural light, and it provided illuminance as much as required through artificial light, thereby saved the lighting energy. The gradation illuminance control was implemented to adjust illuminance of each LED installed in each zone step by step so that lighting energy consumption could be efficiently controlled.

The grid lighting system, proposed in this paper, controlled angles of blinds to secure indoor illuminance by providing maximum inflow of natural light. The control function of the grid lighting was realized so that illuminance in each indoor zone could be maintained to standard illuminance 450 lux. The uniformity was also maintained to higher than 0.3 to provide uniform illuminance to each indoor zone[11]. Meanwhile the color temperature of the lighting was set to be maintained within ±1% of the color temperature of natural light at noon (5400K). Figure 2 shows the processing flow of the proposed lighting system.

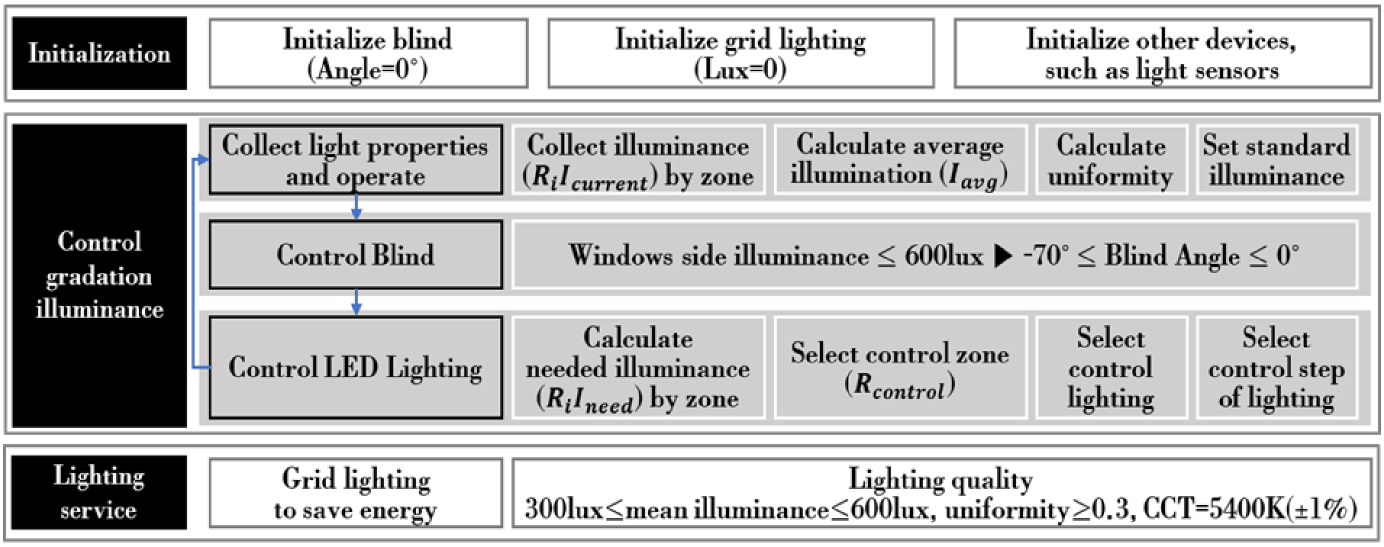


Figure 2. Process flow of grid lighting system

In the grid lighting system in Figure 2, blind angle was set to completely closed (0 degree) and the illuminance of the grid lighting was initiated to 0 lux for all. Then, gradation illuminance control was performed to save lighting energy and to maintain indoor lighting quality. The gradation illuminance control was realized as three-steps of collecting and calculation of light characteristics, blind control, and LED lighting control. During collection and calculation of light characteristics, firstly the illuminance ($R_iI_{current}$) of each zone was measured and the average illuminance of indoor (I_{avg}) was calculated and then compared if each illuminance value exceeded the indoor recommended illuminance level (300-600 lux, as per KS A 3011) [12]. In addition, the uniformity of indoor illuminance environment was calculated to check the illuminance uniformity in each zone. Next was blind control to adjust amount of natural light inflow. The blind slat angle (0-70 degree) was adjusted in real time at 5 degree at each time for maximum inflow of natural light within the range of illuminance of window side not exceeding 600 lux. During controlling LED lighting, illuminance (R_iI_{need}) by zone was calculated and then illuminances for all the zones were compared. The needed illuminance by zone (R_iI_{need}) was calculated from difference between indoor standard illuminance (I_{std}) and current illuminance of each zone as in Equation (1).

$$R_iI_{need} = I_{std} - R_iI_{current} \quad (1)$$

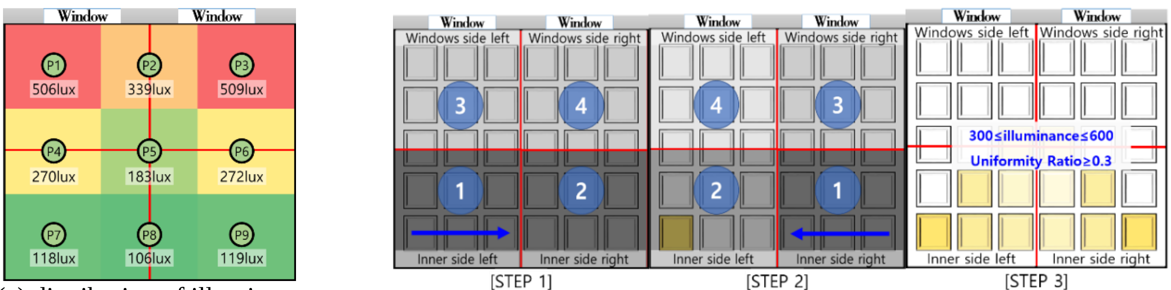
If the indoor average illuminance (I_{avg}) calculated previously was lower than indoor standard illuminance (450 lux), the stepped increase of illuminance was to be executed from the darkest zone where required illuminance was the highest. In the opposite case, a control zone ($R_{control}$) was set to reduce the illuminance from the brightest zone where required illuminance of each zone was the lowest. Therefore, an individual control of LED lighting was realized in the selected zone and for the individual LED control, a control target lighting ($L_{control}$) was selected within the zone. When the required illuminance level in the respective zone was negative, the brightest lighting in the zone was selected. Likewise, when the required illuminance was positive, the darkest lighting in that zone was selected. The formula to select control target lighting ($L_{control}$) is as Equation (2).

$$L_{control} = \begin{Bmatrix} R_iI_{need} < 0, & \max\_lux[L_1, L_2, \dots, L_i] \\ R_iI_{need} > 0, & \min\_lux[L_1, L_2, \dots, L_i] \end{Bmatrix} \quad (2)$$

$(L_1, L_2, \dots, L_i \text{ are the lightings in the control zone})$

The control direction was also considered if multiple lightings with same illuminance might be selected while selecting the target lighting by applying Equation(2). The control direction refers to a control sequence in each zone from the current control zone to the control zone of next priority. In the case of multiple lightings, a farthest lighting from the current control zone was to be selected. After selecting the control zone and the target lighting, the method of increase/decrease brightness of the target lighting was decided. After confirming the currently selected illuminance (brightness), brightness was adjusted step wise. Each LED lighting was set to make the illuminance controlled to a total of 64 steps from 0 lux till 830 lux, and these illuminance levels were applied for gradual brightness control of the individual LED lighting.

While adjusting the illuminance, abrupt increase or decrease of illuminance was avoided not to cause discomfort to occupants. In addition, the color temperature during the lighting control was maintained within 5400K±1. Figure 3 shows the implementation procedure of the proposed lighting control.



(a) distribution of illuminance

(b) Control by lighting and by zone

Figure 3. Control procedure of grid lighting

Figure 3 shows the example of gradation illuminance control during arbitrary time that affected indoor illuminance due to inflow of natural light. Figure 3 (a) shows the distribution of illuminance formed indoor by external natural light. Although illuminance in the zone of window side was secured, inner zone was generally dark, therefore the required illuminance value was positive. Figure 3 (b) presents the control procedure of grid lighting system from STEP1 to STEP3, and the zones in ①~④ during STEP1 and STEP2 were marked as priority control zones. The control order (direction) was decided sequentially from the zone with the lowest illuminance. The STEP1 was selected as a top priority zone which is the darkest since INNER_SIDE_LEFT zone had the lowest illuminance level. Whereas, after deciding the control direction of the lighting to next darkest zone, the lighting control function by each control zone was realized. At this time, by checking the lighting status of LEDs in each zone, LED lighting which was farthest from the indoor center and has the lowest illuminance was searched and it was selected as a target control lighting to perform lighting control. In STEP2, the control zone with a top priority was changed to INNER_SIDE_RIGHT and repeated the priority control zone selection and lighting control by zone. Finally, just like STEP3, the indoor lighting environment was made to comply the recommended illuminance (300-600 lux) and uniformity (0.3). In addition, the color temperature was maintained to 5400K(±1%). Meanwhile, the blinds were controlled at 10 min. interval and grid lightings were controlled at 30 seconds interval. By repeating this process, even if the influence of the incoming natural light on the room changed due to the position of the sun and the weather, it has realized lighting control that provided a uniform light quality and saved energy in the room.

3. EXPERIMENTS AND EVALUATION

An experiment was conducted to check energy saving effect through the proposed system of gradation illuminance method. The experimental environment was constructed as in Figure 4.

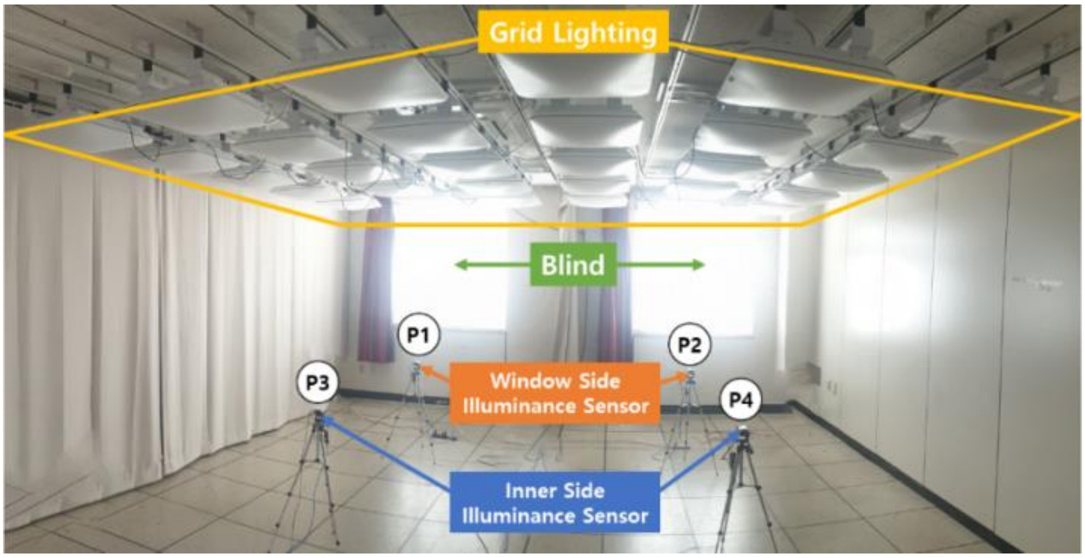
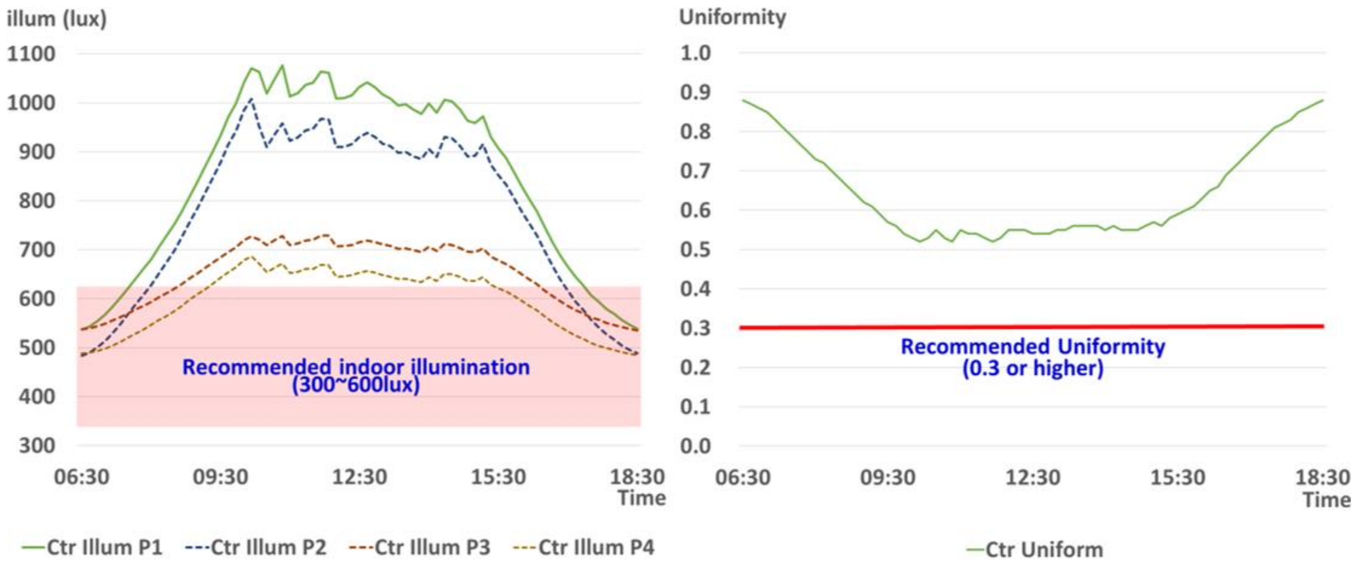


Figure 4. Experimental environment

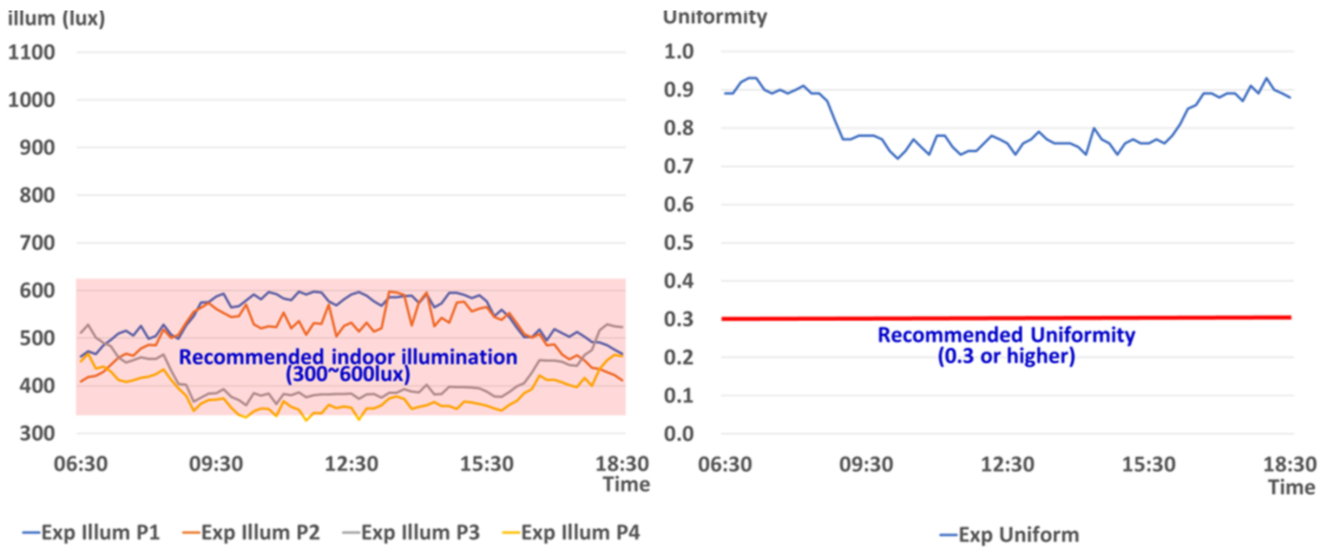
In the experimental space of the grid lighting of dimension 630×720×270cm (W×D ×H) with a total of 30 LEDs in 5x6 matrix structure was constructed on the ceiling surface. Each LED lighting was realized to control illuminance 0-830 lux and color temperature 2600-7400K. Illuminance sensors (TSL 4531) were installed at the height of 85 centimeter (KS C 7612) vertically from the floor in four indoor zones, while the blinds that could be controlled in the range –70°~70° at 5° interval were installed in the windows. The experiments were performed with an experimental group where the proposed system was applied and a control group where four LEDs of illuminance 500 lux vertically from 150 centimeter from the floor considering general office environment. During experiment, the same blind control condition was maintained for experimental group as well as the control group so that both conditions were not influenced by natural light. The experimental results are as in Figure 5.

Figure 5 (b) shows the experimental results obtained under the proposed grid lighting system and these met indoor recommended illuminance requirements in all the zone of windows and inner side for all the time slots even if the effects by natural light during a day changed. In addition, it provided the indoor with uniform light of average higher than 0.8. Whereas Figure 5 (a) in control group shows the illuminances exceeded recommended illuminance in all the zones of window as well as inner side for almost all the time slots. That too, illuminance higher than required was provided to window side rather than inner side. Furthermore, the uniformity calculated as average 0.65 was lower than that of experimental group, confirming that experimental group could make more uniform light environment. The lighting energies incurred from experimental and control group were calculated and compared as shown in Figure 6.

In the control group, which was similar with general office environment, the lighting energy consumption was about 105Wh per 30 min, totaling 1304.43Wh from sunrise till sunset. While, in the experimental group with the proposed lighting system, by conducting gradation illuminance control that provided illuminance differentially according to the distribution of illuminance for each indoor zone, a total of 1000.5Wh was consumed from sunrise till sunset. Especially, at the culmination time where natural light inflow was the largest, the power consumption per hour decreased to about 30Wh, saving power consumption about 70% of the control group, and as far as power consumption for a whole day was concerned, it could save 23% of power compared with the control group.



(a) Control Group



(b) Control Group

Figure 5. Illuminance and uniformity data

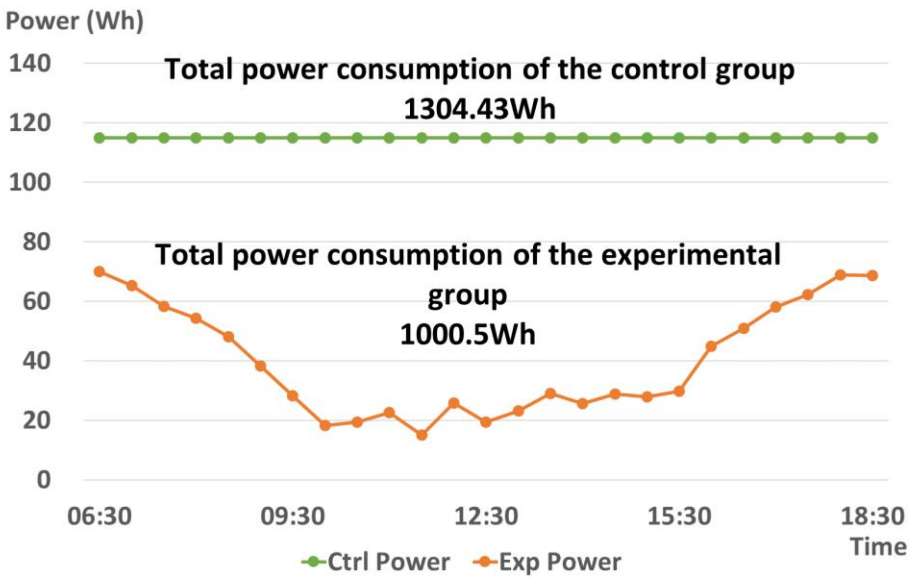


Figure 6. Comparison of lighting energy consumption

4. CONCLUSION

In this paper, a grid lighting system that realizes gradation illuminance control for power saving is proposed considering changes of illuminance distribution in each indoor zone, that keeps changing at each moment due to inflow of natural light. The grid lighting system was constructed with M x N LEDs that could be installed in a broad area on the ceiling and were controlled individually, four illuminance sensors to measure illuminance in each indoor zone, blinds that adjusted inflow amount of natural light through windows, and a Zigbee based gateway and a control server to collect sensing data and to control lightings. The grid lighting control function was realized by maintaining illuminance at each indoor point to indoor recommended illuminance (300-600 lux) while adjusting natural light inflow through the blinds as much as possible, and by complying recommended uniformity (0.3), and by maintaining the color temperature of the lighting to 5400K (±1%). Therefore, the proposed system was constructed by dividing indoor space into four equal areas viz., left, right as well as window side and inner side from the window. The illuminance levels in each zone were measured along with average illuminance in the entire indoor space. The illuminance control was then decided through the comparison with the standard illuminance (450 lux). In addition, the needed illuminances for each zone were calculated. The illuminance was controlled in such way that when the illuminance was to be increased, control was performed for the darkest zone, while if illuminance was to be lowered, the illuminance was controlled from the brightest zone. After selecting the target lighting in the selected each zone, the gradation illuminance control was realized step by step that controlled illuminance of the individual lighting. Furthermore, the gradation illuminance control was operated all the time in response to changes of inflow natural light, thus excessive illuminance supply through lighting was avoided resulting saving lighting energy. In the experiment to confirm energy saving effect by the proposed system, the experimental group with the proposed lighting system could save lighting energy about 23% compared with the control group where general lighting environment was implemented.

Additional experiments considering seasonal changes and climate conditions as well as research for efficient control algorithm of grid lighting by applying deep learning method etc. would be needed in the future. In addition, efforts should be made to maintain not only illuminance but also color temperature of indoor lighting environment to improve functions of grid lighting system.

5. ACKNOWLEDGMENT

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