



Overall Illuminance Uniformity of IRED Lighting in Nighttime CCTV

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This study looks at optimizing light redistribution to improve the overall illuminance uniformity of commercial IRED modules. To obtain uniform illumination over a prescribed rectangular area, a freeform surface lens was evaluated using TracePro. The LED light overall illuminance uniformity regulated in KSC 7658 was verified using Relux software. Experimental test results showed 0.81 overall illuminance uniformity for rectangular light distribution of LED lights having a radiation angle of 80°. After fabricating prototype IRED lights based on these simulation results, illuminance performance was observed when used as actual IRED lighting with a nighttime CCTV system. Image observation photographs of the prototype 80° rectangular IRED lights confirmed that object images can be seen clearly owing to high overall illuminance uniformity, and that dark regions of the CCTV screen were not shown.

Keywords: Light emitting diode, Uniform illuminance, Freeform surface lens, IRED lighting, Overall illuminance uniformity

1. INTRODUCTION

LEDs (light-emitting diodes) are superior to the conventional light bulbs and florescent lights in terms of low power dissipation, high efficient and longer lifetime. Therefore, conventional light bulbs are gradually being replaced by LED light bulbs as the next generation lighting source. LEDs are also playing more important roles in industrial applications, such as backlighting in LCD displays, street lights and interior illumination.

However, LED light bulbs have some problems. Shorter lifetimes and degraded light efficiency occur due to increased heat radiation. This is caused by 70~80% of the supplied power being converted into heat energy. The high heat radiated from a LED light is transferred directly to the LED modules, and light emission efficiency is reduced by this heat generation. As a result, its lifetime

is shortened. Furthermore the size of the LED module becomes much larger, and the manufacturing cost is higher, owing to the required installation of a heat sink in the LED module.

In a closed circuit TV (CCTV) system installed outdoors in the dark or inside dark buildings, its CCD(charge coupled device) camera cannot recognize objects like the human eye can in low illuminance situations. In order to compensate for this, an IRED (infrared emitting diode) is installed or a CCTV system with built in IRED is used. However, since infrared illuminance is too low, or the overall illuminance is not uniform, infrared light is irradiated in one region or the center of the CCTV screen. As a result, image center is bright, but the outer part of the image is dark. This makes it difficult to distinguish some objects. This is the reason for the 'white spot' (saturation of light) caused by the difference of luminous flux intensity between its center portion and outer frame [1]. Other distorted images may be caused by blooming and smearing that degrades image quality [2]. Also, most LED light patterns are circularly symmetric with non-uniform illuminance distribution. This makes it hard to meet the requirement of illumination for nighttime CCTV systems.

In order to solve these problems, this study designs a freeform surface lens to obtain better uniform illuminance over a prescribed

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rectangular area. To simplify the following description, all freeform surface lens of solid objects herein have both inner and outer surfaces.

The prototype IRED lights were fabricated based on results evaluated through the simulation of freeform surface lens. In order to observe their illuminance performance, prototype IRED lights were used as actual IRED lighting for a night time CCTV system. Image observation photographs, captured by the CCD camera using IRED lights, were investigated.

2. THEORETICAL ANALYSIS

2.1 Freeform surface lens design methodology

During the past few years, some freeform surface lens designs have been proposed. Most of the research has been based on freeform surface reflectors [3,4]. However, the target plane uniformity is not good enough. Reflective surface efficiency is not very high, since it is impossible to cover the whole source emergence spatial angle without any occlusion. Because of this, a lens based on refraction and/or total internal reflection of the freeform surface lens has an potential advantage [5-7].

In general, luminous intensity is maximized in the normal direction of the LED source, due to unique LED light distribution characteristics. Luminous intensity becomes smaller in accordance with the incremental increase of the LED source radiation angle. Therefore, its overall illuminance uniformity (U_o) is reduced greatly. This means that the lens design is required to be irradiated in the normal direction of the light source when light is emitted into the air from a optical medium with a large radiation angle.

The light distribution curve varies with the refractive index of the lens. This means that a freeform surface lens design must have an appropriate refractive index, since the lens efficiency is reduced if the refractive index is large. For this reason, the inner surface of a solid object should be formed with a concave surface having two or more the curvature radiuses in order to induce the luminous flux to go in the normal direction of the target plane. Consequently the freeform surface lens was designed to optimize its light redistribution to improve its overall illuminance uniformity for commercial LED lighting. Light energy efficiency was maximized by forming a diffusion on the solid object's outer surface with another concave surface corresponding to the inner concave surface.

To do this, the freeform surface lens was constructed (using Snell's law [8]) based on the grid division method [8,9] within a specific coordinate system. This was established by the relationship between the light source surface and the target surface grid. According to the characteristics of the LED source and the target surface, a space spherical coordinate system and rectangular coordinate system were selected for the source and target, respectively.

First, the design approach sets up the energy conservation relationship between the LED source and the target plane. Then the point coordinates and normal vector \vec{N} of the freeform surface lens were calculated.

According to the coordinates of two points, we obtain the unit vector \vec{I}_n for the incident direction and the unit vector \vec{O}_m for the refraction direction. Then the unit normal vector \vec{N} of the initial point was calculated by the formula of refraction law as shown in equation (1)[8]:

$$\vec{N} = \frac{\vec{O}_m - n \cdot \vec{I}_n}{[1 + n^2 - 2n \cdot (\vec{O}_m \cdot \vec{I}_n)]^{1/2}} \quad (1)$$

Where n is the refractive index of the freeform surface lens.

In this case, the LED source is located at the origin of the

coordinate axis. The luminous flux (Φ) of the LED light sources can be calculated by equation (2) as follows [9],

$$\Phi = \int_0^{2\pi} d\varphi \int_0^{\frac{\pi}{2}} I(\theta) \sin(\theta) d\theta \quad (2)$$

where φ and θ are the horizontal and vertical variable radian angles of a space hemispherical coordinate system, respectively. I_0 is chosen according to the energy relationship between source and target, which is the luminous intensity in the normal direction of the source surface. $I(\theta) = I_0 \cdot \cos(\theta)$, and φ and θ change from 0 to 2π , and from 0 to $\frac{\pi}{2}$ radian angle, respectively. According to the principle of energy conservation [9]:

$$\int_0^{\frac{\pi}{2}} d\varphi \int_0^{\theta(i)} I_0 \cos(\theta) \sin(\theta) d(\theta) = ab \left(\frac{i}{n}\right)^2 E_o \quad (3)$$

A series of values from equation (3) were found by the principle of energy conservation. The ranges of φ and θ values can be obtained, when it is assumed that average target surface illuminance is E_o , and the grid length and width are a and b , respectively. It should be noted that the light illuminance distribution design for the rectangular target surface by the grid division method is very cumbersome due to the complexity of calculations described above.

TracePro was used to evaluate the lens profile pattern based on these results calculated with the grid division method. Then, a 3D freeform surface lens model for rectangular light distribution was designed.

2.2 Simulation of freeform surface lens

The freeform surface lens was designed to optimize the radiation characteristics of the LED source using TracePro release 7.7.2. This simulated the distribution of luminous intensity, irradiance/illuminance, and flux throughout the selected surfaces by tracing rays using the Monte Carlo method [10]. All light rays coming out from the LED source were analyzed by the divergence half-angle ($\phi/2$) [11] over the range of $0^\circ \leq \phi \leq 90^\circ$. The LED power source was located at the origin of coordinates. The initial point (0, 0, 10) was selected, namely, the lens height was 10 mm [9].

A 1x18 W/1980 lm powered lamp was selected as the luminaire equipment for light ray tracing, and around 18,000 rays were traced. It was assumed that the polymethyl methacrylate (PMMA) lens, with a refractive index of 1.4952, passed the light without loss (transmittance was 1).

Phillips' high powered Luxeon3535TX, IREDs (one of the most popular types), were used as luminaire equipment, and simulated the illuminance distribution on a rectangular target at 10m for the simulation dimension (diameter/height) of the light source $\phi 1 \text{ mm} \times 1 \text{ mm}$. It was assumed that Phillips' LEDs were an ideal point source because they have a small optical device chip size, and all light rays from the source would be irradiated at the target plane. The luminous intensity of the optimized lens mounted chip was assumed to be equivalent to that obtained in the far field [12].

2.3 Overall illuminance uniformity

Even though human eyes can recognize objects in a low illuminance situation, CCD cameras without LED lights are not functional enough. Also, CCD cameras with LED lighting can lead to a sleep disorders. During surveillance, criminals are able to avoid detection owing to position exposure of the CCD camera. When the light is irradiated as a inscribed circle on the CCTV screen, it shows a 'white spot' and a blind region. Meanwhile, when the light is irradiated as a circumscription on the CCTV screen, it has uniform light distribution, but its illuminance is lower. Also, much more electric power is consumed by outgoing light to the screen. CCD

cameras can't clearly recognize the protruding portions of objects owing to the 'saturation of light'.

Because of these LED light problems, there is a need for research into the light redistribution on prescribed rectangular areas [13]. It is also necessary to improve overall illuminance uniformity (U_0) when IREDs are used as a nighttime CCTV lighting source.

In this study, overall illuminance uniformity (minimum illuminance/average illuminance) of LED lights was evaluated utilizing the Relux light simulation tool. This is an optical performance prediction program using the IES file of Phillip's Luxen3535TX LED module, where the IES file was very similar to an IES file obtained by the grid division method. In order to obtain uniform illumination on a prescribed rectangular area (L:5 m, W:10 m), the distance between the light source and target plane was changed to the range of 5 m to 20 m.

The experimental LED light tests with various lens radiation angles were focused on uniform illumination of a 15 m × 12 m rectangular area with the target set at 20 m from the light source. The light distribution of some selected LED lights was compared with commercial LED lights, and then to these experimental test results to verify that the lighting conditions (U_0) satisfied KSC 7658 regulations.

Finally, the prototype IRED lights were fabricated based on the simulation results. In order to observe the illuminance performance when the prototype IRED lights were used as actual IRED lighting in a nighttime CCTV system, some Image observation photographs were captured and investigated using the CCD camera with different kinds of IRED lights.

3. EXPERIMENTS

3.1 Simulation analysis of freeform surface lens' design

The freeform surface lens models were designed using a 3D modeler for rectangular light distribution, and the simulated rectangular light illuminance distributions are shown in Fig. 1 and Fig. 2, respectively.

The 3D model of the optimized freeform surface lens with a 80° radiation angle for rectangular light distribution is shown in Fig. 1.

Figure 2(a)-(d) show some simulated rectangular light illuminance distribution characteristics of LED lights obtained from freeform surface lens having the 80° optimized radiation angle. These characteristics were simulated using TracePro, which is a comprehensive software tool for modeling light propagation in imaging. The following simulated results are for light illuminance distributions in a rectangular target area 20 m × 10 m set at 8 m from the light source.

Figure 2(a) shows the map of total irradiance/illuminance. From this map, it can be seen that the rectangular light distribution pattern is very close to that of the lens' design' goal.

Figure 2(b) shows the rectangular candela distribution plot that appears from the horizontal scans of light distribution obtained from the optimally designed freeform surface lens. This plot shows that the luminous flux being reduced in the normal direction of target plane. Therefore, it is also expected that overall illuminance



Fig. 1. 3D model of optimized lens for rectangular target.

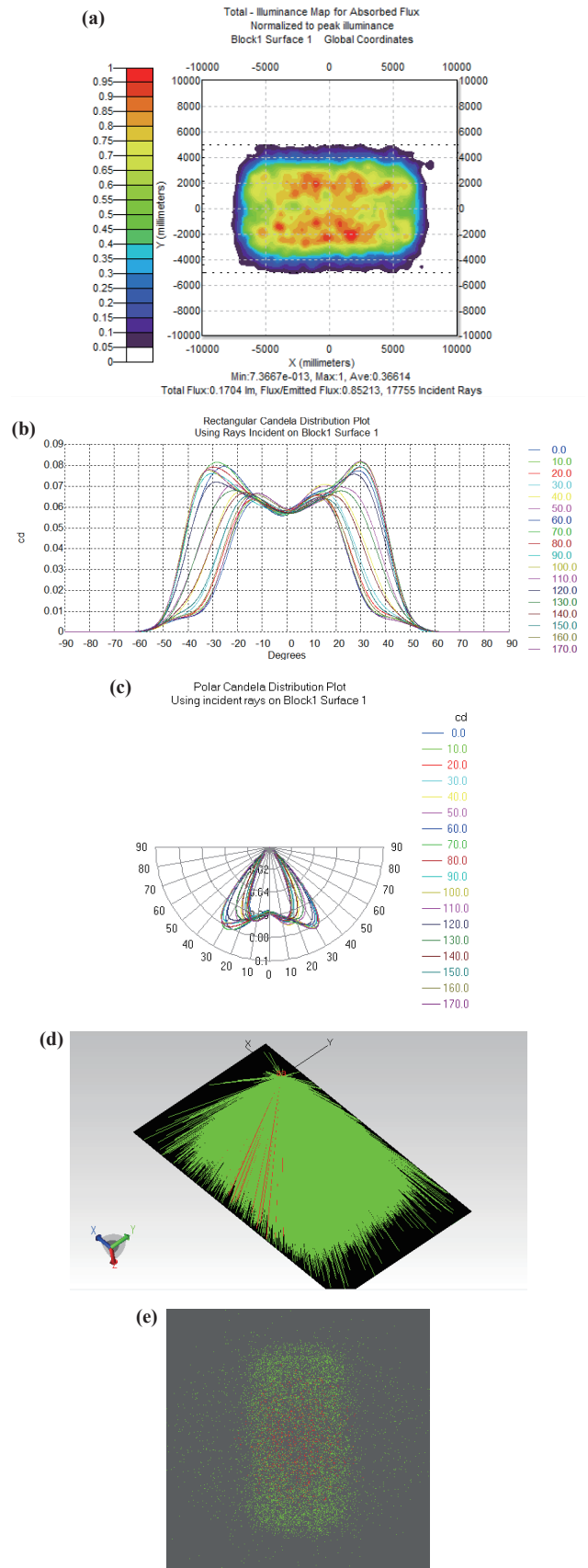


Fig. 2. Simulated rectangular light distribution characteristics through freeform surface lens having radiation angle 80° of (a) total irradiance/illuminance, (b) horizontal candela distribution plot, (c) polar luminous intensity candela distribution graph, (d) light rays, and (e) density of light ray distribution.

uniformity (U_0) of LED lights will be enhanced by eliminating 'saturation of light' against objects.

Figure 2(c) shows the polar luminous intensity candela distribution graph that is very close to the rectangular light distribution pattern required by the freeform surface lens' design' goal.

Figure 2(d) shows light rays that radiate in the direction of the target plane from the LED light source.

In order to definitely see the light rays shown in Fig. 2(d), the light ray distribution density that radiates from LED light source is shown in Fig. 2(e). From these plots, it can be seen that reduced luminous flux goes in the normal direction of target plane compared to other directions. This is the reason it is required to obtain the rectangular light distribution pattern to enhance the overall illuminance uniformity (U_0) of LED lighting.

Figure 2(a)~(e) show that the simulated results meet the requirements for external illumination, and it seems that the uniformity of illuminance distribution will be maintained at a high level.

3.2 Simulation analysis of overall illuminance uniformity

The overall illuminance uniformity (E_{min}/E_{av}) of the freeform surface lens with a radiation angle 80° and rectangular light distribution was evaluated using the Relux light simulation tool, through the IES file of Phillips' LED module. The following simulated results show that the position of the object luminaire is set by the target area $x=10$ m, $y=5$ m. The photometric center height of z is changed to 5 m, 9 m and 20 m.

Figure 3(a)~Figure 3(f) show the simulated results when Phillips' LED lights were embedded into the freeform surface lens, with a 80° radiation angle and rectangular light distribution.

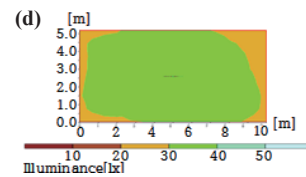
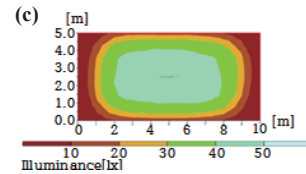
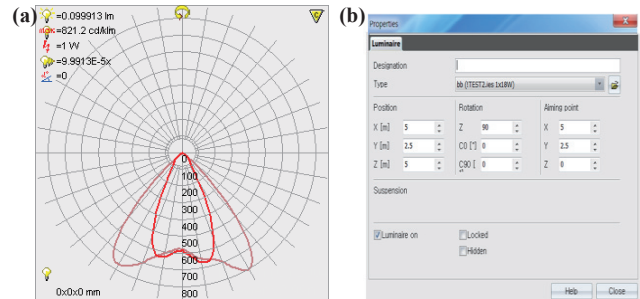
Figure 3(a) shows the luminous intensity distribution curve of the Phillips' high powered Luxeon3535TX file source. It can be seen that it reduces the luminous intensity to go in the normal direction (radiation angle is 0°) of target plane. From this curve, it seems that overall illuminance uniformity (U_0) of the LED lights could be improved by making the rectangular light distribution pattern as described previously. The maximum luminous intensity of the Phillips' power source file was 821 (cd/klm) as shown in Fig. 3(a).

Figure 3(b) is a table of properties of a luminaire set by the position of an object luminaire, $x=10$ m, $y=5$ m and $z=5$ m.

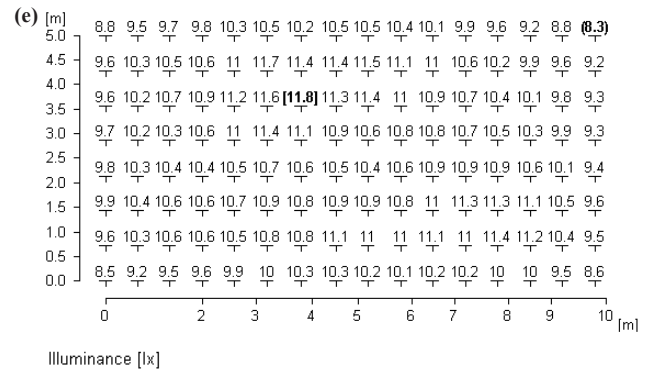
Figure 3(c) shows the properties of a luminaire set by the position of an object luminaire, the target area $x=10$ m, $y=5$ m and $z=5$ m. In this simulation, overall illuminance uniformity ($U_0=0.11$) of an object luminaire is very low if the photometric center height is 5 m. While, average illuminance was a little high 19.7 lx. But, we can see that the luminous intensity distribution pattern is very close to the rectangular light distribution pattern. The maximum and minimum of illuminance, shown in table chart of simulated illuminance were 37.4 lx and 2.1 lx, respectively.

Figure 3(d) shows the properties of a luminaire set by the position of the object luminaire, the target area $x=10$ m, $y=5$ m, and $z=9$ m. These are the properties when the photometric center height is changed to 9 m. From these simulated results, the overall illuminance uniformity (U_0) of the selected object luminaire was 0.80 higher than that of Fig. 3(c). Then, average illuminance (E_{av}) of the object luminaire obtained was lower 10.4 lx than that of Fig. 3(c). The luminous intensity distribution pattern still remains close to the rectangular light distribution pattern.

This is the reason why rectangular light distribution patterns can enhance the overall illuminance uniformity (U_0) of an object luminaire. The maximum and minimum of illuminance, shown in the table chart of simulated illuminance were 11.8 lx and 8.3 lx, respectively.



General	
Calculation algorithm used	Average indirect fraction
photometric centre height.	9.00 m
Maintenance factor	0.75
Total luminous flux of all lamps 1980 lm	
Total power 1.0 W	
Total poere per area (50.00 m²) 0.02 W/m² (0.19 W/m²/100lx)	
Evaluation area 1	
Em	10.4 lx
Emin	8.3 lx
Emin/Eav (Uo)	0.80
Emin/Emax (Ud)	0.70
Position	0.00 m
Reference plane 1.1	
Horizontal	
Uniformity : 0.8	



Height of the reference plane	
Average illuminance	Eav : 10.4 lx
Minimum illuminance	Emin : 8.3 lx
Maximum illuminance	Emax : 11.8 lx
Uniformity Uo	Emin/Eav : 1 : 1.25 (0.80)
Diversity Ud	Emin/Emax : 1 : 1.43 (0.70)

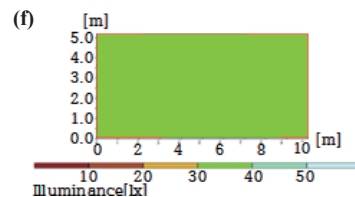


Fig. 3. Simulated results of radiation angle 80° rectangular light distribution of (a) luminous intensity distribution curve, (b) properties of luminaire, (c) uniformity at $z=5$ m, (d) uniformity at $z=9$ m, (e) illuminance table chart of Fig. 3(d), and (f) uniformity at $z=20$ m.

For the reference, Fig. 3(e) shows the simulated illuminance table chart of Fig. 3(d), which is represented by the same numerical data of the reference plane shown in Fig. 3(d). According to the table chart, the maximum and minimum illuminances were 11.8 lx and 8.3 lx, respectively.

Figure 3(f) shows the properties of a luminaire set by the position of the object luminaire, the target area $x=10$ m, $y=5$ m, and $z=20$ m. These are the properties when the photometric center height is changed to 20 m. As a simulated result, the overall illuminance uniformity (U_0) of an object luminaire was 0.95, higher than that of Fig. 3(d).

The reason for that is based on the following. It was assumed that light can pass through the PMMA lens, having the refractive index of 1.4952, without any loss (transmittance is 1), and it was also assumed that all rays of light radiated from the source will be irradiated to target plane. For simplicity in the simulation process, these conditions were assumed even though actual reality is not so.

The average illuminance (E_{av}) obtained for an object luminaire was lower (2.21 lx) than that of Fig. 3(d). From this result, the CCD camera captured a clear image of an object under this illuminance. The overall illuminance uniformity of LED lights increased a little when the distance between the LED lights and the target increased, even though the illuminance of the IRED lights decreased.

From these results, it can be confirmed that the illuminance uniformity was more than 0.80, when the distance is in the range from 9 m to 20 m. This uniform illumination over the prescribed rectangular area satisfies the lighting conditions ($U_0>0.4$) regulated in KSC 7658.

4. RESULTS AND DISCUSSION

4.1 Experimental results of overall illuminance uniformity

The following test results show the luminous intensity

distribution curve and overall illuminance uniformity of a rectangular 15 m × 12 m target area, set at a distance of 20 m from the light source. The maintenance factor of all testing objects was set at 0.75 according to KSC 7658. Figures 4–6 show the test results obtained by commission from the authorizing agency, KTR (Korea Testing & Research Institute).

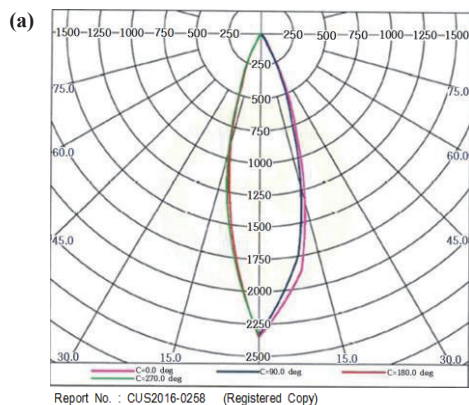
Figure 4(a) shows the test results of a commercial 30° circularly light distribution product. From the luminous intensity distribution curve, it can be seen that maximum luminous flux goes in the normal direction of the target area. This is the cause of the ‘white spot’ (saturation of light) in a CCD camera as described previously.

In Fig. 4(b), you can see that overall illuminance uniformity shown in the test report was 0.14. This test result is not enough to recognize an object in a CCTV system. Therefore, overall illuminance uniformity needs to improve when LEDs are used for CCTV lighting. The illuminance of commercial lights are a little low at 1.93 lx.

Figure 5(a) shows the experimental results when rectangular LED light distribution is embedded into the optimally designed prototype freeform surface lens having a radiation angle of 80°. In this curve, we can see that it is less the luminous flux to go in the normal direction of target plane. This causes the increase in overall illuminance uniformity on the CCTV system as described above.

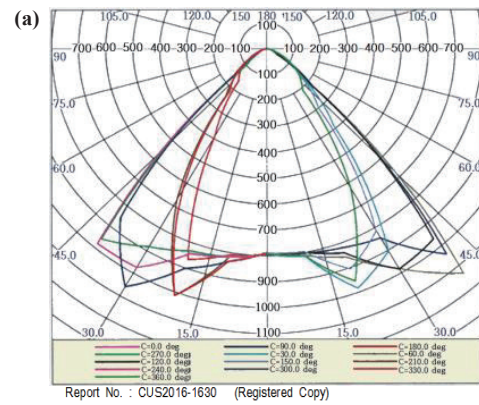
In Fig. 5(b), it can be seen that overall illuminance uniformity of the rectangular 80° light distribution was 0.81, and the illuminance of our prototype lights was almost the same value (1.91 lx) as the commercial 30° circular light distribution products (1.93). These results show much improvement in overall illuminance uniformity compared to that of commercial circular 30° products and other illuminance uniformity ($U_0=0.56$) of rectangular light distribution LED lighting [14]. Image captured from the CCD camera against the object could be seen more clearly. Consequently, it seems that our rectangular 80° light distribution lights will be applicable for the CCTV system.

Figure 6(a) shows the test results of our prototype rectangular light distribution with a radiation angle of 120°. From this curve,



Test Results

Test Items	Unit	Test result	Remarks
Light Distribution	-	Refer to 3 page	-
Average Illuminance	lx	1.93	-
Uniformity	-	0.14	-

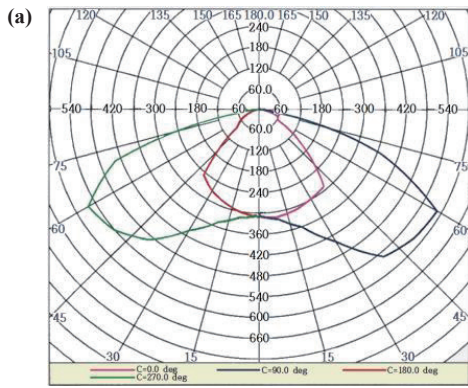


Test Results

Test Items	Unit	Test result	Remarks
Light Distribution	-	Refer to 3 page	-
Average Illuminance	lx	1.91	-
Uniformity	-	0.81	-

Fig. 4. Circularly light distribution curve of commercial IRED lights having radiation angle of 30° : (a) luminous intensity and (b) test results.

Fig. 5. Rectangular light distribution curve of our LED lights having radiation angle of 80°: (a) luminous intensity and (b) test results.



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Test Results

Test Items	Unit	Test result	Remarks
Light Distribution	-	Refer to 3 page	-
Average Illuminance	lx	0.53	-
Uniformity	-	0.85	-

Fig. 6. Rectangular light distribution curve of our IRED lights having a radiation angle of 120°: (a) luminous intensity and (b) test results.

Table 1. Experimental test reports of overall illuminance uniformity and average illuminance against lens type.

Lens type	Commercial circularly 30°	Our circularly 52° lights	Our rectangular 80° lights	Our rectangular 120° lights
Overall illuminance uniformity	0.14	0.72	0.81	0.85
Average illuminance (E_{av})	1.93	2.05	1.91	0.53

we can see that it also is less the luminous flux to go in the normal direction of a target area like Fig. 5(a). For that reason, the overall illuminance uniformity of rectangular 120° lights was a little higher (0.85) than that of the rectangular 80° lights as shown in Fig. 6(b). Nevertheless, the average illuminance (E_{av}) of the luminaire was too low at 0.53 lx. As a result, this product is not suitable for the nighttime CCTV lighting.

The overall illuminance uniformity (U_0) and average illuminance of experimental test reports of commercial luminaires and some kinds of prototype products are tabulated in table 1.

As shown in Table 1, the experimental test report of overall illuminance uniformity(U_0) of our rectangular 80° light distribution was a little low at 0.81 compared to that of its simulated results (0.95) as shown in Fig. 3(e).

The reason for the high simulated result is as follows. It was assumed that the light passes through the PMMA lens without light loss in the simulation process. In actuality, light can't pass through a PMMA lens without loss, and its transmittance won't be able to be 1. It would be closer to 0.91-0.94.

It was also assumed that all rays of light radiated from the LED source could irradiate the target plane. Actual LED light conditions differ from the simulation, because all light rays passing through freeform surface lens and external waterproofing cover are scattered by absorption, transmission, reflection and refraction.

Theoretical analysis of the low experimental test results compared to the simulated results will be studied further in future work.

4.2 Illuminance performance observation of IRED lights

The prototype 24 W IRED luminaires based on the simulated freeform surface lens were fabricated, considering its heat radiation characteristics. When our prototype IRED lights were used as actual IRED lighting for a nighttime CCTV system, its illuminance performance was observed. Some Image observation photographs were captured by the CCD camera using different kinds of IRED lights as shown in Fig. 7- Fig. 8.

Objects 1, and 2 were a person standing 10 m and 15 m away from the CCD camera. Images were taken at Busan INJI elementary school. Other than moonlight, there was no external illumination. The CCD camera was a Hanhwa Techwin SNO6011 with a mounted 3.8 mm fixed lens, WDR, and a minimum Illuminance of lux 0.

4.2.1 Image observation of object

Figure 7 shows image observation photographs captured by the CCD camera against object 1 at the distance 10 m from the camera.

Figure 7(a) shows a photograph of object 1, using a commercial 60° circular IRED products of company P. In Fig. 7(a), the object's coat can't be distinguished due to the 'white spot' phenomenon. Furthermore there are many dark regions on the CCTV screen.

Figure 7(b) shows a photograph of object 1, using our prototype 52° circular IRED lights. The coat image can be seen more clearly compared the image in Fig. 7(a). Some dark regions on the CCTV screen still remain.

Figure 7(c) shows a photograph of object 1, using our prototype 80° rectangular IRED lights. Here, the coat image is also clearer than the image in Fig. 7(a), and there are even less dark regions than in Fig. 7(b).

This is because the overall illuminance uniformity was enhanced by eliminating the saturation of light against the subject in CCTV through the design of freeform surface lens. As a result, we were able to see a clear picture screen. Furthermore, no dark region of the CCTV screen owing to the improved high overall illuminance uniformity was shown.

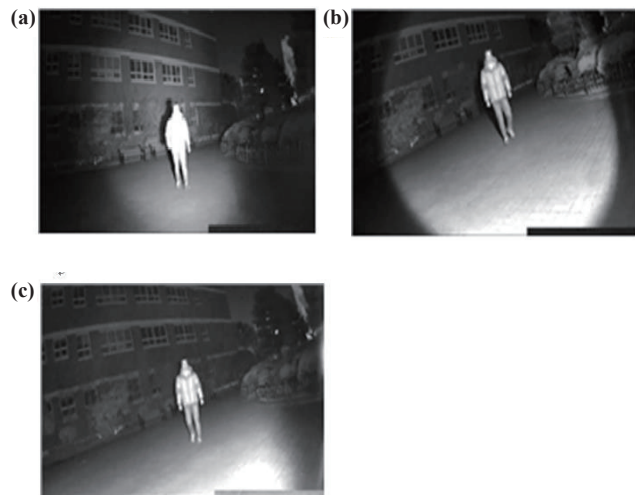


Fig. 7. Image observation photograph of object 1 with (a) 60° circularly, (b) 52° circularly, and (c) 80° rectangular.

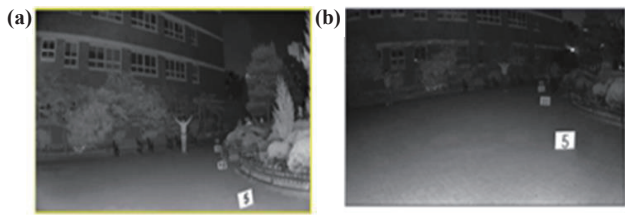


Fig. 8. Image observation photographs of object 2 with (a) 80° rectangular and (b) 120° rectangular.

4.2.2 Image observation of object 2

Figure 8 shows some image observation photographs captured by the CCD camera against object 2 at the distance 15 m from the camera.

Figure 8(a) shows a image observation photograph of object 2, using our prototype 80° rectangular IRED lights. The image is clear and no dark regions show on the CCTV screen owing to the improved high overall illuminance uniformity that was shown in Fig. 7(c).

Figure 8(b) shows a photograph of object 2, using our prototype 120° rectangular IRED lights. Here, we can't clearly see the image of object 2. This is caused by the decreasing illuminance of the prototype 120° rectangular IRED lights. No dark regions on the CCTV screen were due to the improved high overall illuminance uniformity shown in Fig. 7(c).

From these results, the optimized prototype lights have a high potential for use as IRED lighting with nighttime CCTV.

5. CONCLUSIONS

A Freeform surface lens was designed for rectangular illuminance distribution in order to enhance the overall illuminance uniformity ($U_{\sigma}=E_{\min}/E_{\text{av}}$) of IRED lights. Their illuminance performances were observed when prototype IRED lights were used as actual IRED lighting for a nighttime CCTV system. Summarized experimental results are as follows.

First, the simulated rectangular light illuminance distribution characteristics of an LED lights obtained from optimally designed freeform surface lens having radiation angle 80° was evaluated by utilizing TracePro. The results in the luminous intensity distribution pattern were close to the rectangular light distribution pattern. The Trace Pro analysis confirmed to be reduced the luminous flux goes in the normal direction of target plane. This improved the overall illuminance uniformity of the LED lights. Consequently, the light distribution pattern of the simulated results was in good agreement with the required freeform surface lens' design' goals.

LED light Overall illuminance uniformity (U_{σ}) was evaluated with the Relux light simulation tool. Simulated results of LED lights with a 80° radiation angle lens were investigated. The overall illuminance uniformity of its LED lights was larger than 0.80, when the distance between the LED light source and the target plane was in the range from 9 m to 20 m. These LED light simulation results satisfied the lighting conditions ($U_{\sigma}>0.4$) regulated in KSC 7658.

Second, test results of overall illuminance uniformity on the

rectangular 15 m × 12 m target area, set at a distance from the LED light source of 20 m were as follows. The maintenance factor of all testing objects was set at 0.75. The best experimental test reports of overall illuminance uniformity of rectangular light distribution products having radiation angle 80° lens was 0.81 (obtained from the Korea Testing & Research Institute). This was much improved result compared to other illuminance uniformities ($U_{\sigma}=0.56$) of rectangular LED lighting distributions. This result indicates that freeform surface lens can be maintained at the high level.

Finally, nighttime CCTV lights were fabricated with prototype 24 W IRED lights based on simulated results using TracePro and Relux(with consideration for heat radiation characteristics). Image observation photographs were captured by the CCD camera using three kinds of prototype IRED lights. They were compared with commercial 60 circular IRED lights. The experimental test results of all prototype IRED lights satisfied the lighting condition ($U_{\sigma}>0.4$) of LEDs regulated in KSC 7658. The image observation photographs of the prototype 80° rectangular IRED lights confirmed that the image can be seen clearly. Overall illuminance uniformity was enhanced by eliminating the saturation of light against the object on the CCTV screen due to the design of freeform surface lens. No dark regions showed on the CCTV screen due to the high overall illuminance uniformity. These results were quite consistent with the expected goal.

In conclusion, it was confirmed that the rectangular illuminance distribution through the freeform surface lens was designed adequately to get high overall illuminance uniformity (E_{\min}/E_{av}) of IRED lights.

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