Daylight Performance of Horizontal Light Pipe with Egg-Crate Reflector in the Tropics

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Daylight Performance of Horizontal Light Pipe with Egg-Crate Reflector in the Tropics

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Abstract. Horizontal Light Pipe (HLP) is one of a light transport system that can guide daylight deeper into building interiors. Improvement of HLP, focusing on its opening distribution was proposed in this study. An egg-crate reflector was installed at HLP's opening distribution to achieve a uniform light distribution inside office space. The aim of this study was to evaluate and explain the daylight performance of HLP with an egg-crate reflector at office space in the tropics. Experiment with physical scaled model 1:5 was used as a research method. Illuminance value, Daylight Factor (DF), uniformity ratio and diversity of illuminance of an office space lit by side window (base case) were compared to the office space lit by side window and HLP with an egg-crate reflector (case), simultaneously with daylighting standards. The results showed that the integration of HLP and egg-crate reflector improved both daylight level and distribution. Improvement of DF and illuminance level were in the range of 16.6% to 56.6%. Uniformity ratio of the base case was in the range of 0.35 to 0.45, while the uniformity ratio of the case was in the range of 0.48 to 0.66. Application of HLP with an egg-crate reflector decreased the diversity of illuminance and resulted in more uniform daylight distribution inside space. The diversity of illuminance of the base case at a low altitude of the sun (15:00) exceeded 5:1 while the diversity of illuminance in the case was kept lower than 5:1 at all the measurement time.
Keywords: Daylight performance, egg-crate reflector, horizontal light pipe, tropics

1. Introduction

Daylighting application in a building gives several benefits to building occupants. According to Alrubaih et al., [1], daylighting is an important strategy to achieve visual comfort and reduce building energy consumption. Daylight is expected as the best light source for good color rendering. Quality of daylight is also the one light source that is the most probable equivalent of human visual response [1]. The use of daylighting inside building reduces not only the energy use for electric lighting but also the whole building energy use [2].

According to IAE [3], daylighting design in the tropics is focused on preventing overheating by restricting the daylight entering a room. The necessity to minimize solar heat gain in a modern air-conditioned office building in the tropics results in severe externally shaded windows or highly reflective glazing with severe internal shading [4]. The plan of an air-conditioned building also has a tendency to be deep [5] with a minimum surface area to volume ratio to reduce heat load from building envelope [6]. The utilization of daylight in building then minimal even though the ambient illuminance levels are high. Daylight level at building interiors distant from the side window is low since the daylight level decreases rapidly when the distance from the window increases.

Innovative daylighting systems have been developed to deliver daylight deeper into building interiors, at the same time reducing the overheating problem [7]. Horizontal Light Pipe (HLP) is one of a light transport system that can guide light into the depth of the room [8]. Horizontal Light Pipe collects, redirects the daylight using aperture located at building facade, transports daylight to the building interior through a pipe and distributes it to the building interior via opening distribution. Daylight through the light pipe can complement that from sidelighting in the deep interior of a building [9].

Several strategies to improve the daylight performance of Horizontal Light Pipe were studied. Those studies including the use of two statics and tiltable mirror [10], central and side reflectors, trapezoidal shape in plan [11] [12] [13], laser cut panels [14] [15] and a flat captation system [16]. Improvement of HLP daylight performance also studied by combining HLP with another daylighting strategy such as optical light shelf [17], reflective louver [18]. Those strategies showed the ability of Horizontal Light Pipe in improving daylight level and distribution at a deep area of the building.

Further improvement of HLP's light distribution devices and light emission within the space are needed [15]. Another strategy which is focusing on Horizontal Light Pipe's opening distribution is proposed in this research. HLP's opening distribution is usually formed by a diffuser with an 88% transmittance [11] [17], diffuser with a translucent Mylar film with a VT of 70% [12], translucent sheets [9], clear glazing with 84% transmittance [10] or Laser Cut Panel [14]. Different from previous research, integration of transparent opening distribution with an egg-crate reflector is proposed in this study. Application of egg-crate reflector is expected to distribute daylight uniformly. The aim of this study is to evaluate and explain the daylight performance of HLP with an egg-crate reflector at office space in the tropics.

2. Horizontal Light Pipe with Egg-crate Reflector

Horizontal Light Pipe (HLP) is one of Light Transporting Systems [7] that can collect sunlight from building façade through an aperture, transport it through the pipe and distribute it through opening distribution to the deep area of the building. The aperture is designed using a transparent material, which is a clear glass with Visible Transmittance of 88% and equipped with a reflector to collimate the incident sunlight to the back of light pipe before distributed to the room by opening distribution. The reflector in this study is static and tilted in response to the daily, seasonal range of sun position of Surabaya (latitude 7.21° S and longitude 112.54°E). Located in the tropics, the aperture of HLP faces either East or West [9]. In this study, the aperture of HLP is oriented to the West to utilize the sunlight from noon to evening.

The pipe is a rectilinear duct that has optical properties appropriate to deliver sunlight into the room [16]. Material which is used inside the pipe is mirror acrylics that has a specular reflectivity of 85%. The pipe has a trapezoidal shape in plan and tapered from the aperture towards the end of HLP. The length and height of the pipe are 9.3 m and 0.70 m, respectively. The width of the pipe from aperture to the middle part of the pipe is 2 m. The pipe is then tapered and has a width of 1 m at the back of the room. The light pipe design in plan and section is shown in figure 1.

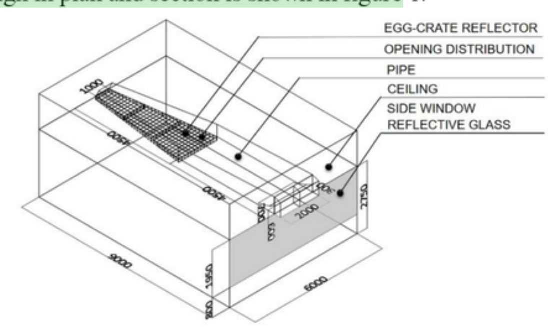


Figure 1. The configuration of the horizontal light pipe

The opening distribution is designed to be integrated with an egg-crate reflector. Clear glass is used as the material of HLP opening distribution to maximize the light transmittance from HLP to the room. An egg-crate reflector then installed at the opening distribution area to improve the uniformity of daylight distribution.

The egg-crate reflector is a louvered construction divided into cell-like areas and used for redirecting the light emitted by an overhead source [19]. Louvers reflector is used to shield against direct glare [20]. An analysis of glare possibility in the visual field was conducted to determine the height, width, and distance between each sheet of the egg-crate reflector. The direct view of the light sources from the Horizontal Light Pipe was shielded up to 30° (figure 2)

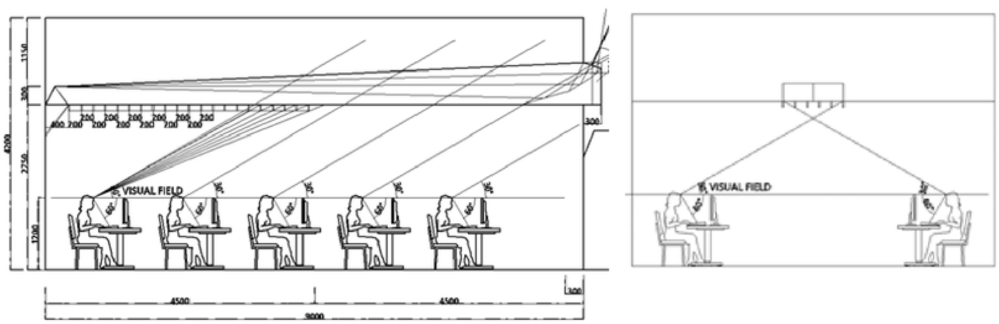


Figure 2. Analysis of glare possibility in visual field to determine egg-crate reflector's size

Methodology

Experiment with physical scaled model 1:5 was used as a research method to study the daylight performance of Horizontal Light Pipe (HLP) with the egg-crate reflector. The scaled model approach is an effective tool for the study of daylight performance of buildings and requires accuracy in the model construction [21] [22]. A scale model also describes the distribution of daylight within the model as exactly as in a full-size room when properly constructed [23]. Illuminance value, Daylight Factor (DF), Uniformity Ratio and diversity of illuminance of an office space lit by side window (base case) were compared to the office space lit by side window and HLP with an egg-crate reflector (case), simultaneously with daylighting standards (table 1).

Experimental tests were conducted in 7th roof deck at P building of Petra Christian University, Surabaya (latitude 7°14' S, longitude 112°45' E) under real sky condition. Two physical scaled models were built to represent an office space with a side window (base case) and an office space with side window and HLP with an egg-crate reflector (case) (figure 3).

The physical scaled model represented an office space, which had 6 m in width and 9 m in length. The ceiling height of the office space was 2.75 m. The wall and floor of the model were constructed using Glass-fiber Reinforced Cement (GRC) boards and galvalume hollow frames. The interior surface of the model, including floor, wall, and ceiling were painted. Interior surface reflectance of the floor, walls, and ceiling were 0.43, 0.66 and 0.74 sequentially. The office space had a side window facing west and used a reflective glass (stopsol super silver dark blue) 6 mm with Visible Transmittance of 36%. The side window had 6 m in width and 1.95 m in height.

A Horizontal Light Pipe (HLP) with an egg-crate reflector was installed at the plenum of the test room (case). The HLP was constructed using plywood and had 9.3 m in length and 0.7 m in height. The width of the pipe from the aperture to the middle part of the pipe was 2 m. The pipe then was tapered and had a width of 1 m at the back of the room. Mirror acrylics with a specular reflectance of 85% were covered the interior surfaces of the pipe while a single clear glass 3 mm was covered the aperture (table 2).

The egg-crate reflector had 4.5 m in length and 2.10 m in width. Each unit of the reflector had 0.15 m in height, 0.15 m in width and 0.15 m in length. The material of the reflector was chromed-aluminum. The egg-reflector was mounted at the opening distribution of HLP (figure 4).

Table 1. Experimental scheme

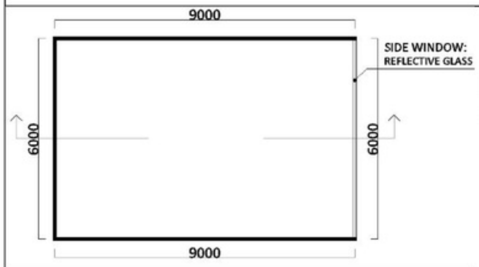
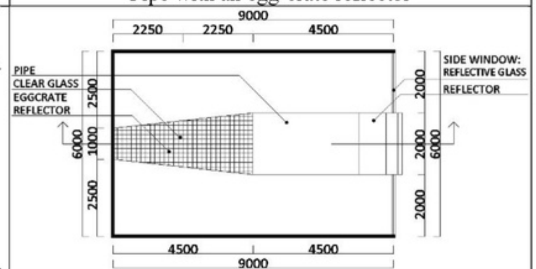
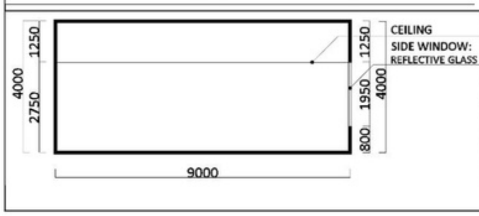
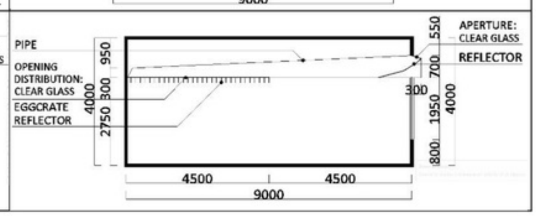
Base Case	**Case**
Office space with side window	Office space with side window and Horizontal Light Pipe with an egg-crate reflector
	
	

Figure 3. Physical scaled model 1:5 to represent office space which are lit by side window and Horizontal Light Pipe with an egg-crate reflector

Table 2. Details of Horizontal Light Pipe and the test room

Test Room		
Surface reflectance	Floor	Reflectance 0.43
	Wall	Reflectance 0.66
	Ceiling	Reflectance 0.74
Side window	Reflective glass (stopsol classic dark blue)	Visible Transmittance 36%
Horizontal Light Pipe with an egg-crate reflector		
Aperture	Clear glass 3 mm	Visible Transmittance 88%
Egg-crate reflector	Mirror acrylic	Reflectance 0.85
Pipe	Mirror acrylic	Reflectance 0.85
Opening distribution	Clear glass 3 mm	Visible Transmittance 88%

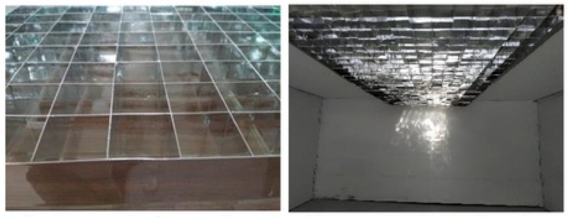


Figure 4. Chromed Egg-crate Reflector Panel at Horizontal Light Pipe's opening distribution

Five HOBO data loggers U12-012 which were designed for indoor measurement of relative light levels were installed at each model. The arrangement of the light meter (HOBO data logger U12-012) is represented in figure 5. Three of HOBO data loggers were arranged perpendicular to the side window, at the center of the room. Two HOBO data loggers were also installed at the distance of 7.5 m from the side window, under the opening distribution in order to study the daylight distribution of HLP. A HOBO Pendant Data Logger UA-002-64 was installed on the top of the model to measure outdoor illuminance level.

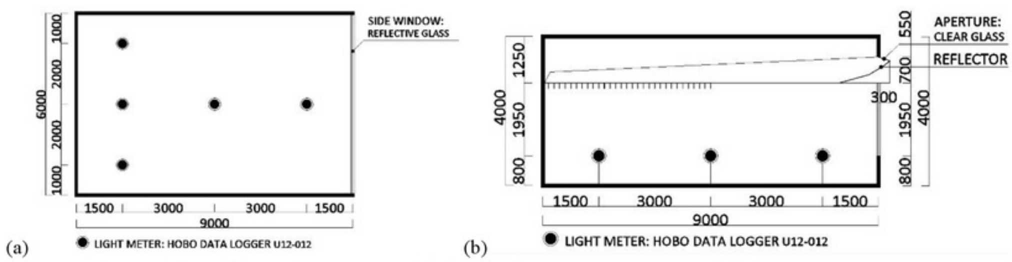


Figure 5. Model configuration (case) with full scale measurements and light meter arrangement; (a) Plan and (b) Section

4. Results and Discussion

4.1. Illuminance Level and Daylight Factor Analysis

Figure 6 shows the average illuminance level of base case (office space with side window) and case (office space with a side window and Horizontal Light Pipe with egg-crate reflector). The results showed that the average illuminance level of both cases was above 500 lux, the typical illuminance recommendation by CIBSE for general offices [24]. The high level of average illuminance in both cases was recorded in the morning (09:00-12.00 h) where there was no direct sunlight and also in noon and afternoon (12:00-16:00 h) where the sun was facing the window.

The highest value of the average illuminance level reached 5,362 lux and 4,506 lux at base case and case, sequentially. The highest level of average illuminance in both cases occurred at 14.30 h when the sun was facing the window. The lowest value of the average illuminance level was 725 lux and 589 lux at base case and case, sequentially. At that time, the side window and Horizontal Light Pipe that were oriented to the West received daylight only.

The average illuminance level of the case was lower than the base case at a low altitude of the sun (09.00-11.15 and 14.00-16.00). The reduction of average illuminance level by HLP with an egg-crate reflector application was in the range of 4.4% to 18.7%. Different tendency recorded at a high altitude of the sun (11:45 to 13:45 h) where the case had a higher average illuminance level than the base case. The improvement of the average illuminance level by HLP and egg-crate reflector application inside office space was in the range of 2.03% to 23.68%. The role of Horizontal Light Pipe and egg-crate reflector in increasing daylight level inside office space was significant at a high altitude of the sun. The highest improvement of the average illuminance level by HLP and an egg-crate reflector was reached at 13:30 h.

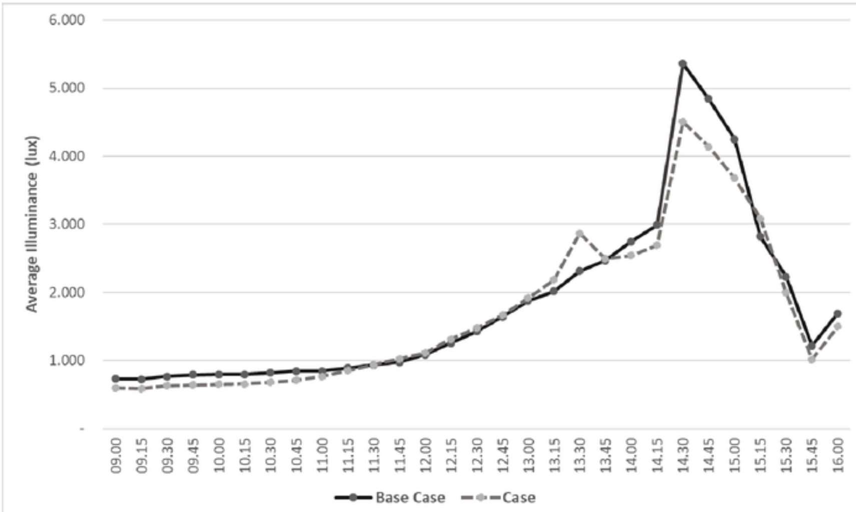


Figure 6. Average illuminance level of office space with side window (base case) and office space with side window and Horizontal Light Pipe with egg-crate reflector (case)

Further investigation about the illuminance level of base case and case in the middle of the space is shown in figure 7. The investigation focuses on illuminance level at measuring point at the distance 7.5 m from the side window, under an opening distribution of HLP with an egg-crate reflector. The results showed that the illuminance level of the case at the distance 7.5 m from the side window was higher than the base case. Illuminance level of the base case was in the range of 485 lux to 1,494 lux at 12.00 to 15.00, while the illuminance level of the case was in the range of 611 lux to 1,746 lux at 12.00 to 15.00. Application of HLP with an egg-crate reflector improved the illuminance level in the deep area of office space as big as 17% to 57%. The highest daylight level improvement of HLP and egg-crate reflector occurred at a high altitude of the sun (13:00 h).

The illuminance level of HLP with an egg-crate reflector at a deep area of the space was above 500 lux and met the typical illuminance recommendation by CIBSE for general offices [24]. This results also answered the role of HLP in addressing the problem of a deep-plan office building in the tropical climates [4].

Figure 8 shows the Daylight Factor (DF) level of base case and case in a deep area of the building, at the distance 7.5 m from the side window. The daylight factor (DF) level of the case was higher than the base case. The DF level of base case were 0.2%, 0.5%, 0.9% and 2.3% at 12.00, 13.00, 14.00 and 15.00, sequentially. The DF level of the case were 0.3%, 0.7%, 1.0% and 2.6% at 12.00, 13.00, 14.00 and 15.00, sequentially. The highest DF level was reached at a low altitude of the sun (15.00) and was met the typical minimum Daylight Factor for offices as big as 2% [20]. Direct evening sunlight entering the light pipe aperture at 15.00 generated high DF value.

The role of HLP with an egg crate reflector in improving the DF level was visible at the deep area of the building. Improvement of DF level by HLP with an egg crate reflector were 26%, 56.6%, 16.6% and 16.9% at 12.00, 13.00, 14.00 and 15.00, sequentially. The highest improvement of DF level was reached at a high altitude of the sun (13:00 h).

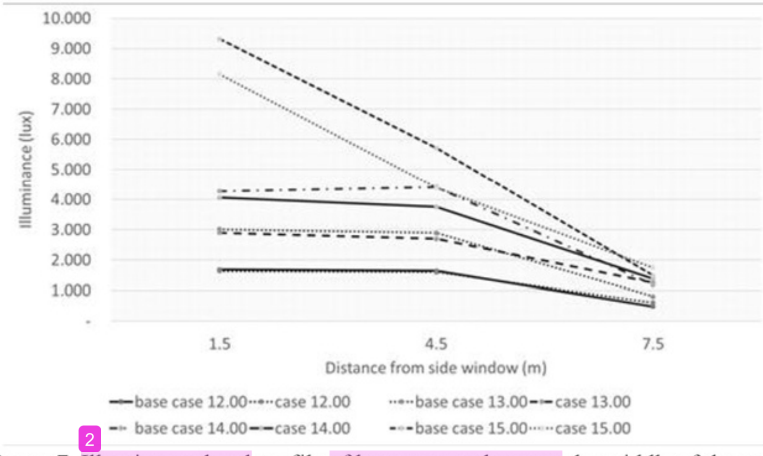


Figure 7. Illuminance level profile of base case and case at the middle of the space

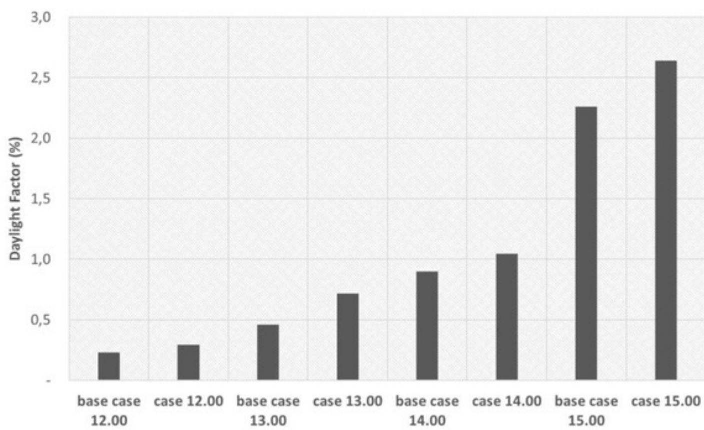


Figure 8. Daylight Factor level of base case and case at 7.5 m from side window

4.2. The Uniformity and Diversity of Illuminance Analysis

The uniformity of illuminance levels describes the quality of lighting space where the subject performs a visual task [25]. The uniformity of illuminance also refers to the illuminance condition on the task and the immediate surroundings [1]. The illuminance uniformity is expressed as a ratio of the minimum illuminance to the average illuminance on a surface according to Equation 1.

$$UR = Emin/Eavg \quad (1)$$

UR = Uniformity Ratio
Emin = Minimum Illuminance
Eavg = Average illuminance

The results showed that application of HLP with an egg-crate reflector improved the illuminance uniformity ratio in a space. Uniformity ratio of the base case was in the range of 0.35 to 0.45, while the uniformity ratio of the case was in the range of 0.48 to 0.66 (figure 9). Improvement of illuminance level at the area distant from side window by HLP and egg-crate reflector application improved the uniformity of illuminance inside space. This improvement of illuminance uniformity is important in relation to the comfort and productivity of the occupants.

The highest uniformity ratio at the case was reached at a high altitude of the sun (13:00 h). The lowest uniformity ratio at the case was reached at a low altitude of the sun (15:00), where direct evening sunlight entering the light pipe aperture and the side window.

The diversity of illuminance shows changes in the illuminance values across a larger space [1]. The diversity of illuminance is expressed as the ratio of the maximum illuminance to the minimum illuminance in the working plane of the main area of space, and should not exceed 5:1 (Hannaford in [1]) as expressed in Equation 2.

$$DI = Emax/Emin \quad (2)$$

DI = Diversity of Illuminance
Emax = Maximum illuminance
Emin = Minimum illuminance

The results showed that office space with side window and HLP with an egg-crate reflector had a lower diversity of illuminance than an office space with side window only (figure 10). The ratio of the maximum illuminance to the minimum illuminance in base case was 3.47:1, 3.69:1, 3.72:1 and 6.23:1 at 12:00, 13:00, 14:00, 15:00, sequentially. The ratio of the maximum illuminance to the minimum illuminance in the case was 2.68:1, 2.31:1, 2.94:1, 4.67:1 at 12:00, 13:00, 14:00, 15:00, sequentially. Application of HLP with an egg-crate reflector in office space decreased the diversity of illuminance in space and resulted in more uniform daylight distribution inside space. The diversity of illuminance of the base case at a low altitude of the sun (15:00) exceeded 5:1 while the diversity of illuminance in the case was kept lower than 5:1 at all the measurement time.

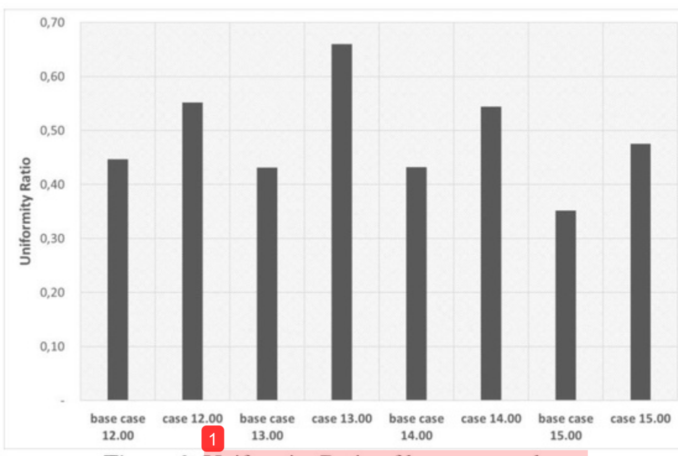


Figure 9. Uniformity Ratio of base case and case

Table 3 illustrates the resultant visual quality of office space with side window only (base case) and office space with side window and HLP with an egg-crate reflector. Application of HLP with an egg-crate reflector increases the daylight distribution inside space by improving the daylight level at an area distant from the side window.

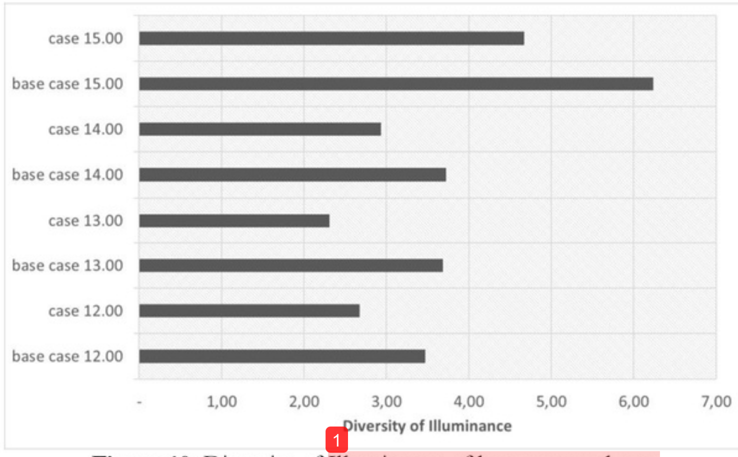


Figure 10. Diversity of Illuminance of base case and case

Table 3. Visual, uniformity ratio, diversity of illuminance of base case and case at 12:00

	Base Case	**Case**
	An office space lit by side window	An office space lit by side window and Horizontal Light Pipe with egg-crate reflector
		
		
Uniformity Ratio	0.45	0.55
Diversity of Illuminance	3.47:1	2.68:1

5. Conclusion

Application of HLP and an egg-crate reflector can introduce adequate daylight level for general offices. The illuminance level and DF of HLP and egg-crate reflector at an area distant from side window were in the range of 611 lux to 1,746 lux and 0.3% to 2.6%, sequentially, at 12.00 to 15.00. Those daylight levels were met the typical illuminance recommendation for general offices. HLP and egg-crate reflector also generated uniform daylight distribution inside office space. The diversity of illuminance was 2.31:1 to 4.67:1, which has met the maximum diversity of illuminance in office space.

Integration of HLP and egg-crate reflector improves the daylight level inside office space, especially at the area distant from a side window. Application of HLP with an egg-crate reflector enhanced the illuminance level in the deep area of office space (7.5m from side window) as big as 16.6% to 57%.

HLP with egg-crate reflector also improved the DF level, reached 56.6% and occurred at a high altitude of the sun (13:00 h).

Application of HLP with an egg-crate reflector (case) resulted in more uniform daylight distribution inside space than an office space with side window only (base case). Uniformity ratio of the base case was in the range of 0.35 to 0.45, while the uniformity ratio of the case was in the range of 0.48 to 0.66. Application of HLP with an egg-crate reflector decreased the diversity of illuminance and resulted in more uniform daylight distribution inside space. The diversity of illuminance of the base case at a low altitude of the sun (15:00) exceeded 5:1 while the diversity of illuminance in the case was kept lower than 5:1 at all the measurement time.

Further investigation on thermal performance and energy efficiency of the proposed HLP with egg-crate reflector is needed.

6. Acknowledgement

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