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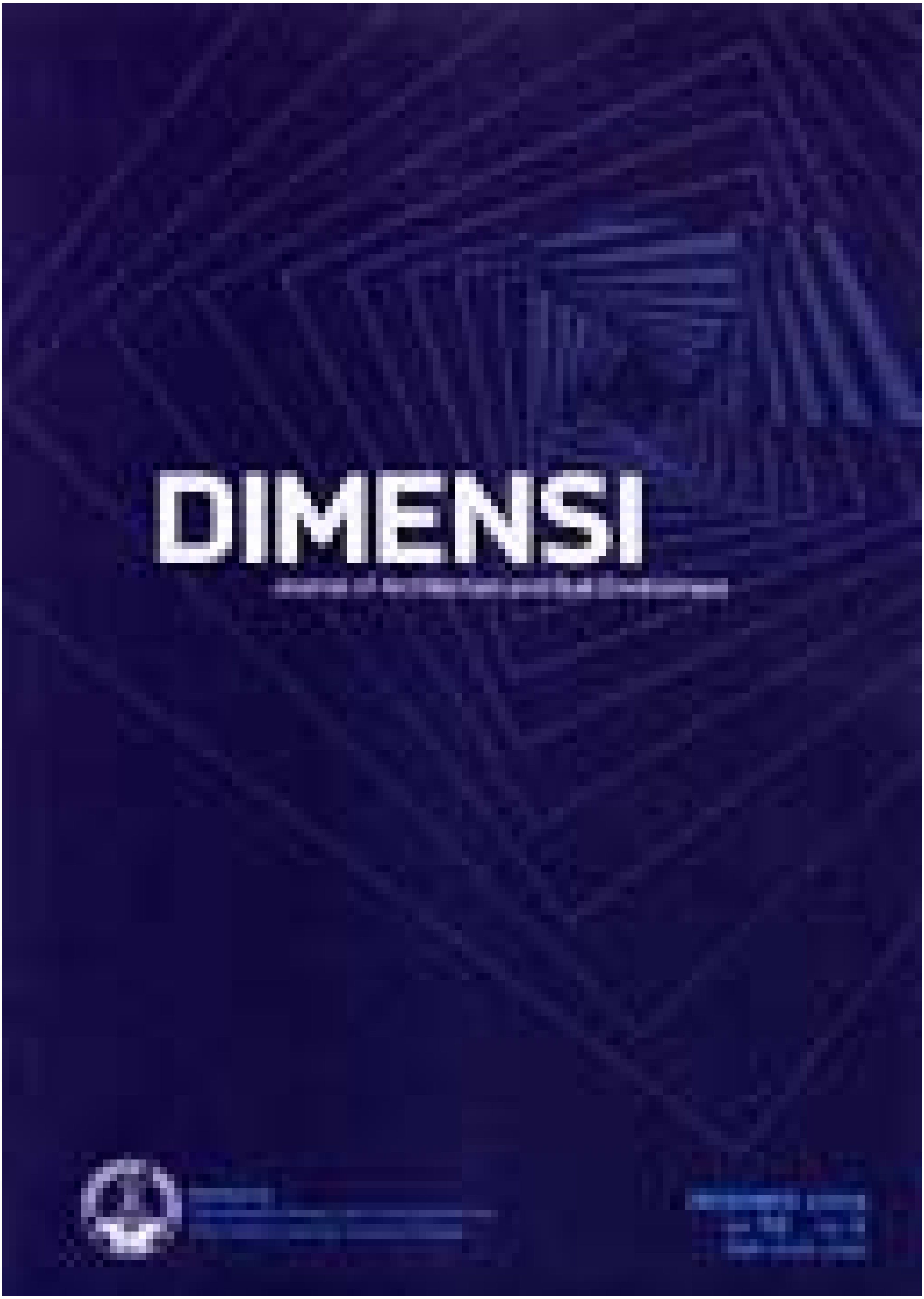

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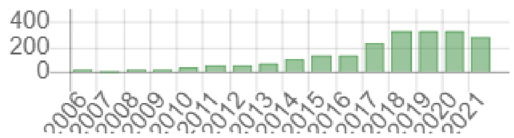

THE EFFECT OF OPENING DISTRIBUTION AREA MODIFICATION ON HORIZONTAL LIGHT PIPE DAYLIGHT PERFORMANCE

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ABSTRACT

The use of daylight within an office building in the tropics provides energy savings, psychological and physiological health advantages for building occupants. In order to promote the daylight admission, the building should have a narrow depth. However, plans of modern air-conditioned buildings tend to be deep, in order to minimize heat gain from the building envelope. A deep plan office building design limits access to daylight and generates an insufficient daylight level on the workspace distant from the side window. Horizontal Light Pipe (HLP) is one of light transport systems that can deliver daylight to these areas. The research aim was to explain and evaluate the effect of HLP's opening distribution area on daylight performance at deep plan-private office space in the tropics. The research method was experiment with simulation as a tool. Daylight level and daylight uniformity of the base case, HLP with an opening distribution area of 6.6 m^2 were compared with the case, HLP with an opening distribution area of 3.41 m^2. The results showed that HLP with a smaller opening distribution area of 3.41 m^2 could illuminate working spaces where a simple visual task is performed. A 50% reduction of HLP's opening distribution area, from 6.6 m^2 to 3.41 m^2 improved average Daylight Factor (DF) as much as 6.42%. The presence of highly specular material on opening distribution area contributed to the specular reflection of daylight before being transmitted to office space by a translucent glass. A lower illuminance uniformity ratio but still meet the recommended illuminance uniformity ratio on workspace was resulted in a smaller HLP's opening distribution area. Considering the improvement of daylight level and high uniformity ratio resulted, HLP with a smaller opening distribution area can be applied as the main source of daylight on deep-plan office spaces.

Keywords: Horizontal Light Pipe; opening distribution area; daylight performance; tropics; office space

INTRODUCTION

The use of daylighting within an office building in the tropics provides energy savings, physiological and psychological advantages for building occupants. Proper utilization of daylighting can reduce energy for electric lights in a typical office building (Lechner, 2015) and also cooling energy consumption (Alrubaih et al., 2013). Daylight provides vitamin D and a well-balanced circadian rhytm (Boubekri, 2008). People also desire good daylighting in their living and working environments (Li and Lam, 2003). Reduction of absenteeism, increase productivity and financial savings are other benefits gained in daylit and full spectrum office building (Edwards and Torcellini, 2002).

According to Heerwagen (2004), in order to facilitate the admission of daylight, the building should have a narrow depth. Extending the perimeter form of a building may improve the building's performance by increasing the total daylighting area (Ander, 2003). However, plans of modern air-conditioned buildings tend to be deep (Lomas, 2007) in order to minimize heat gain from building envelope. Deep-plan office building design limits access to daylighting and generates an insufficient daylight level on the workspace in areas distant from the side window.

Horizontal Light Pipe (HLP) is one of light transport system (Kischkoweit-Lopin, 2002) and is designed to supplement the daylight admitted by a lower vision window and to be the main source of daylight at 4.6-9.1 m from side lighting (Beltran et al., 1997). Aperture, pipes and distribution opening are the main elements of HLP. Aperture collects, redirects or concentrates incident sunlight. Pipes transport the daylight inwards the building, while distribution opening distributes daylight into deep areas of the room (Canziani et al., 2004).

Previous research focused on daylighting performance of HLP had been conducted, such as four types of HLP in 9 m office space (Beltran et al., 1997); flat captation HLP [11]; HLP with tiltable mirror (Hien et al, 2007) and HLP with Laser Cut Panel (Garcia Hansen et al., 2001; Kwok and Chung (2008). The combination of HLP with louver (Elsiana et al., 2015a) and HLP with branching opening distribution (Elsiana et al., 2015b) were also studied. Those research showed the ability of HLP in illuminating space distances from sidelighting.

Different from previous research, a single HLP was applied at a deeper office space (10.5 m). Without any access to sidelighting, HLP in this research acted as the main source of daylight. The research aim was to evaluate and explain the effect of HLP's opening distribution area on daylighting performance at deep plan-private office space in the tropics.

HORIZONTAL LIGHT PIPE IN PRIVATE OFFICE SPACE

HLP type C prototype by Beltran et al., 1997 was used in this study with several improvement and different application. A single Horizontal Light Pipe (HLP) was installed in a deeper room depth (10.5 m), consist of two identical private office spaces. Those private office spaces were located in a tropical area, Surabaya (latitude 7º15' South and longitude 112º44'33''East), under an overcast sky condition.

Placed in a tropical area, HLP's aperture faced West to utilize daylight in the afternoon. This HLP's aperture orientation was in line with the previous research by Chirarattananon et al., 2000 and the nature of the sun path along the tropical area of Surabaya. Figure 1 shows the sun path diagram of Surabaya (stereographic diagram), which was calculated using Ecotect analysis.

Located at the distance of 4.5 m from perimeter window, both spaces didn't have access to sidelighting and depended only on HLP as the main source of daylight. Each room had 3 m in width, 4 m in length and 2.75 m in height, as described at Figure 2 and Figure 3. Those private office spaces were placed at the center of an office building that had 24 m in width and length. Ceiling's reflectance was 85%, while the wall and floor reflectance were 70% and 40%, respectively (Rea in Egan and Olgyay, 2002). This office building was free from shadow casting from adjacent buildings and vegetation.

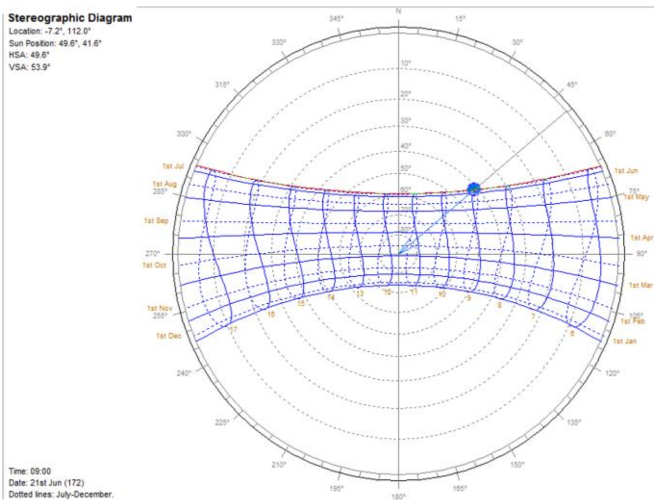


Figure 1. Sun path diagram of Surabaya (latitude 7º15' South and longitude 112º44'33''East)

The HLP had a trapezoidal section both in plan and elevation. The width of HLP's aperture and the rear of HLP were 1.8 m and 0.9 m, respectively. The length of HLP was 10.5 m (Figure 3).

HLP's aperture had 1.8 m in width and 0.6 m in height. The aperture was covered by a single clear glass that had Visible Transmittance (VT) of 88%. In order to redirect incoming sunlight, the aperture was equipped with central and side reflectors which had reflectivity of 88%.

The rectilinear pipe that transports the daylight had 0.6 m in height and was covered by 95% specular reflective film on its surface. The material of opening distribution, a daylight diffuser into a deep area of the building, was a translucent glass that had a transmittance of 88%.

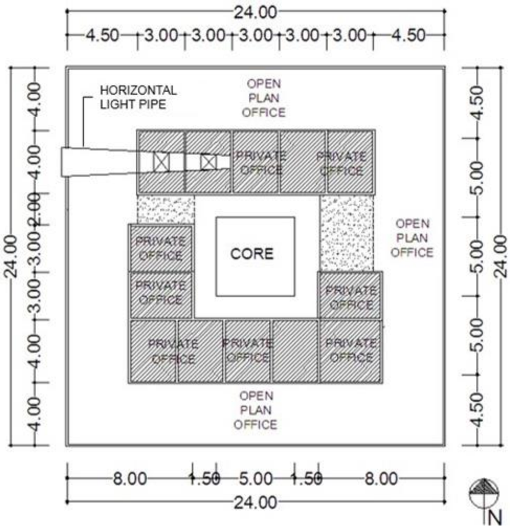


Figure 2. Horizontal light pipe and private office space location in office building

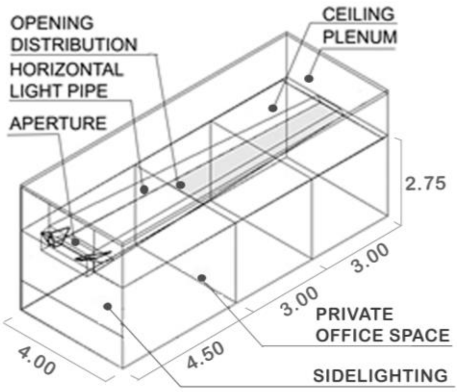


Figure 3. Perspective of a single horizontal light pipe in private office spaces

METHODOLOGY

To study the effect of the opening distribution area on daylight performance at deep plan-private office space, the experimental method with simulation as a tool was used. A radiance-based computer simulation which had been validated in previous research (Canziani et al., 2004 and Courret et al., 1998) was employed. Radiance is a daylighting simulation program that uses a ray-tracing methodology to predict daylight's behavior in space accurately (Canziani et al., 2004). Characteristic of the materials used in this experiment was described in Table 1.

Table 1. Characteristics of Horizontal Light Pipe and Private Office Space

Private Office Space		
Surface reflectance	Floor	40.34% (RAL 7005_mouse grey
	Wall	71% (beige paint)
	Ceiling	85.77% (white)
Sidelighting	WWR	7.1%
	Bronze reflective	Transmittance 22% Reflectance 24%
Horizontal Light Pipe		
Aperture	3 mm clear laminate DuPont	Transmittance 88% Reflectance 8.3%

Opening distribution	3 mm clear laminate DuPont	Transmittance 88% Reflectance 8.3%
Pipe	Galvanized-metal LBNL	Reflectance 97.5% Specularity 80% Roughness 15%
Mirror	Galvanized-metal LBNL	Reflectance 97.5% Specularity 80% Roughness 15%
Reflector	Aluminium LBNL	Reflectance 88.6% Specularity 80% Roughness 2%

Daylight level and uniformity of the base case, HLP with an opening distribution area of 6.6 m^2 were compared with the case, HLP with an opening distribution area of 3.41 m^2, simultaneously with daylighting standards. The base case and case had one opening distribution and two opening distributions, respectively. Those opening distributions were located at the center of each private office space (Table 2).

Location of measurement points inside private office spaces can be observed in Figure 4 and 5. Twelve measurement points were located in each private office space. The measurement points had a distance of 0.50 m from the wall and had a distance of 1 m between one another. The height of measurement points was 0.75 m above floor plan.

Experiment was carried out under overcast sky condition in Surabaya (7º15' South Latitude and 112º44' East Longitude). Illuminance and Daylight Factor were simulated on 21 June at 09.00, when HLP's supplementary illuminance was significant (Chirarattananon et al., 2000).

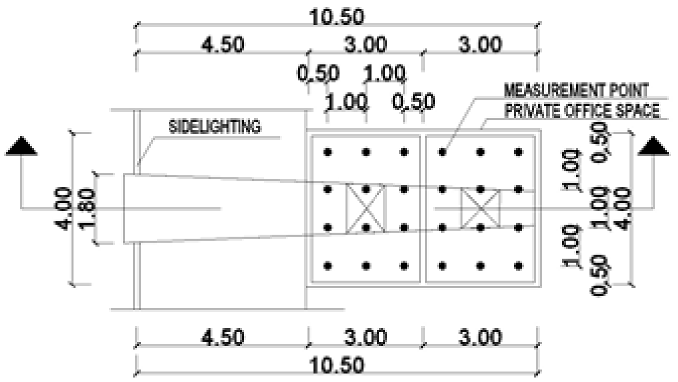


Figure 4 Position of measurement points inside private office spaces (plan)

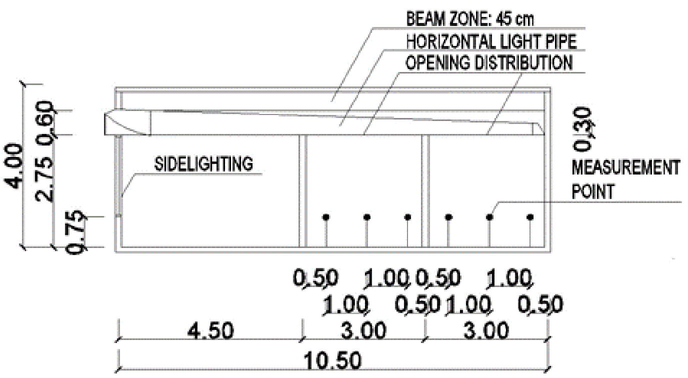
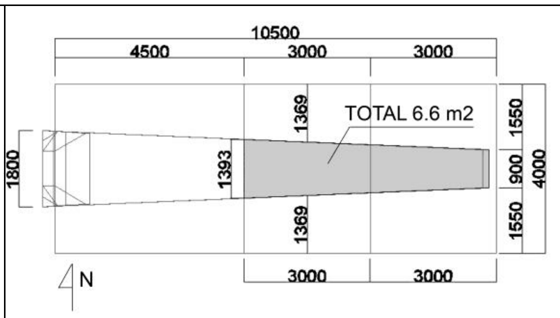
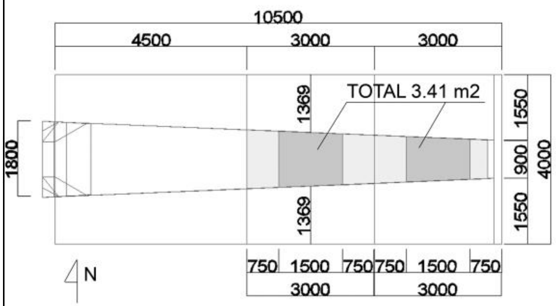


Figure 5 Position of measurement points inside private office spaces (section)

Table 2. Experimental Scheme

Base Case	
	Amount of opening distribution: 1 Opening distribution area: 6.6 m^2
Case	
	Amount of opening distribution: 2 Opening distribution area: 3.41 m^2

RESULTS and DISCUSSION

Daylight performance analysis was done by comparing illuminance level, Daylight Factor (DF) and uniformity ratio of the cases, simultaneously with daylighting standards. Horizontal illuminance guidelines by IESNA in Steffy, 2002 were used as daylighting standards. Horizontal illuminance target value for work area where simple visual tasks are conducted is 135-165 lux. Illuminance uniformity on work space should be 3:1 in average to minimum and 6:1 in maximum to minimum.

Illuminance Level and Daylight Factor

The results showed that HLP with an opening distribution of 6.6 m^2 (the base case) introduced an average work plane illuminance level as big as 127.1 lux. This illuminance level was below the illuminance target value for working space where a simple visual task is performed (135-165 lux) (Steffy, 2002).

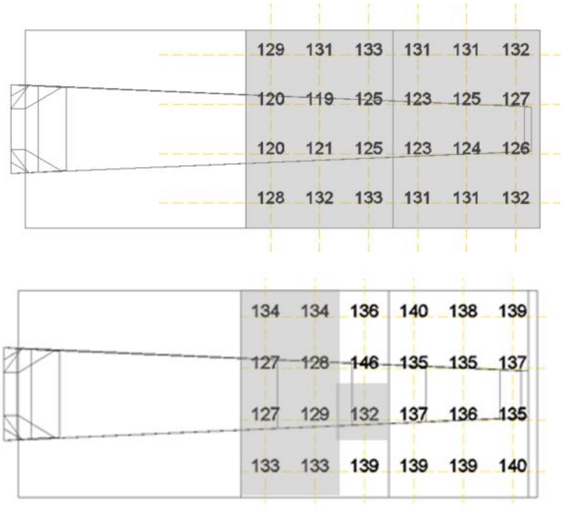
Previous research by Mogo (2005) studied 9 m HLP under the same sky condition, overcast sky, but in higher latitudes (30°36’ N). Slightly reduction of illuminance value compared with Mogo’s light pipe occurred in this research. The reduction occurred because the HLP in this research was longer than Mogo’s HLP.

Reduction as big as 50% of opening distribution area, from 6.6 m^2 to 3.41 m^2 demonstrated an improvement in daylight level. The case (HLP with an opening distribution area of 3.41 m^2) introduced higher average work plane illuminance level than base case (HLP with an opening distribution area of 6.6 m^2). Average work plane illuminance level of the case reached 135.3 lux.

Compared to standards, average work plane illuminance level performed by HLP with the opening distribution area of 3.41m^2 had met the illuminance target value for working space where simple visual tasks are performed (135-165 lux). That office space can accommodate several activities such as casual reading, copy room or as a computer-intensive office (Steffy, 2002).

To investigate the daylight performance of HLP with different opening distribution area thoroughly, the analysis also performed on illuminance value at all measurement points inside space. Figure 6 shows that illuminance value on all measurement points with HLP’s opening distribution area of 6.6 m^2 was below the illuminance target value for work area where a simple visual task is conducted (135-165 lux). A single HLP which had opening distribution area of 6.6 m^2 could not function as working space where simple visual tasks are performed.

Different results occurred at office space with HLP’s opening distribution area of 3.41m^2. Illuminance value at most of the measurement points inside office space was in the range of the illuminance target value for work area where a simple visual task is conducted (135-165 lux). That improvement of illuminance level occurred mostly on deeper office space, at the distance of 6-10.5 m from sidelighting.



(a)

(b)

= illuminance value < 135 lux

Figure 6 Illuminance value on private office space with HLP's opening distribution area of (a) 6.66 m2 and (b) 3.41 m2

Figure 7 shows the percentage of measurement points which had illuminance value under and above the illuminance target value for working area where simple visual tasks are conducted (minimum 135 lux). For the base case, illuminance level on all measurement points inside space was under 135 lux. This result indicated that the office space could not be functioned as a working space where simple visual tasks are performed.

Different results appeared in the case, where the illuminance level on 62% measurement points inside rooms was above 135 lux and had met the illuminance target value for working space where simple visual tasks are performed (135-165 lux). Those measurement points mostly located in deep office space, at the distance of 6-10.5 m from side window.

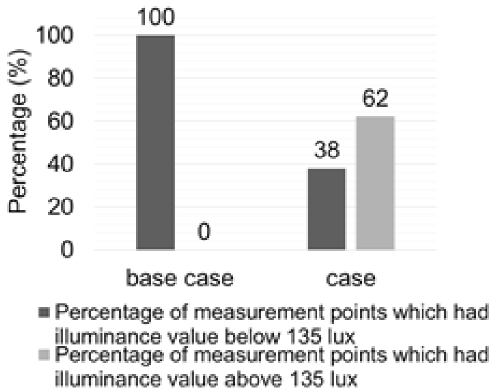


Figure 7 Percentage of measurement points which had illuminance value below and above 135 lux

HLP with an opening distribution area of 6.6 m2 introduced average DF as big as 1.27% while HLP with an opening distribution of 3.41 m2 introduced average DF as big as 1.35%. These values were below the typical minimum DF for offices, as big as 2% (Lechner, 2015).

The Effect of Opening Distribution Area on Illuminance Level and Daylight Factor

The results indicated that with the same quantity and length (10.5 m), HLP with a smaller opening distribution area placed at the centre of the space had a higher average illuminance level and DF than HLP with a larger opening distribution area (Figure 8). A 50% reduction of HLP's opening distribution area increased average DF as much as 6.42%.

Improvement of average illuminance level and Daylight Factor (DF) of HLP with a smaller opening distribution area is a new finding. This results showed a different tendency with previous research conducted by Beltran et al., 1997 about HLP's opening distribution area. Improvement of daylight level in previous research was achieved not only by enlarging opening distribution area, but also adding side reflectors and applying a trapezoidal section of HLP (Beltran et al., 1997). In this research, without any change in HLP's reflector and section, a 50% reduction of opening distribution area increased the daylight level as much as 6.42%. The presence of highly specular material on the opening distribution area had a contribution in specular reflection of daylight before being transmitted to office space by a translucent glass.

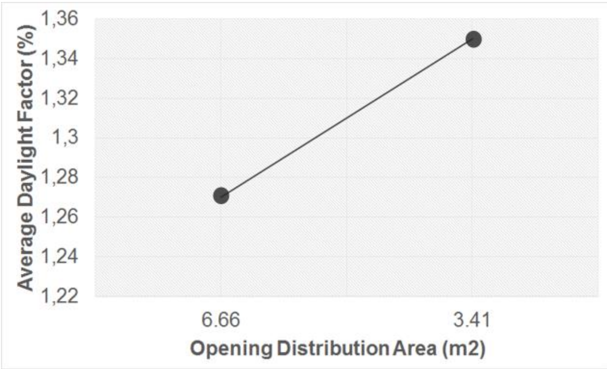


Figure 8 The effect of opening distribution area on average Daylight Factor (DF)

Figure 9 indicates DF profile (%) of the base case and case at the center of the office space. HLP with a smaller opening distribution area (3.41 m^2) had a higher DF level than HLP with an opening distribution area of 6.66 m^2. The improvement of Daylight Factor (DF) value of HLP with a smaller opening distribution area was in the range of 5.6% to 11.4%. The results showed the role of a highly specular material in reflecting the daylight before being transmitted to the office space.

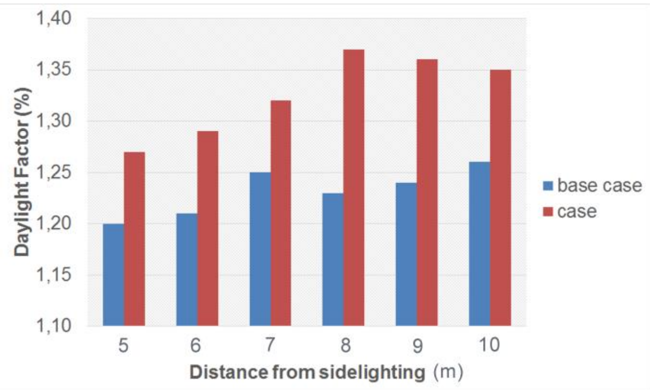


Figure 9 Daylight Factor profile of base case and case at the center of the office space

The profile also shows that in general, DF from Horizontal Light Pipe increased towards the interior of the room (Figure 9). This results had a good agreement with the previous research by Chirarattananon et al., 2000 about the pattern of daylight level from a light pipe.

Figure 9 also showed that improvement of DF level occurred in the area adjacent to the back walls. This improvement reached because the light came from opening distribution was reflected off the wall and increased DF level near to it, in accordance with the results of Beltran et al., 1997 study.

Further observation showed that base case and case had different DF profile under HLP's opening distribution area. DF profile of HLP with an opening distribution of 6.66m^2 was similar, i.e. increased towards the back of each office space. Different DF pattern was resulted by HLP with an opening distribution of 3.41 m^2, where DF profile of deeper office space, in the distance of 7.5-10.5 m from side lighting was higher than office space at the distance of 4.5-7.5 m from side lighting. The shape of HLP which tapers out towards the back of the space and the presence of highly specular material on the opening distribution area had a role in improving DF level.

Daylight distribution

Analysis of daylight distribution was conducted by comparing illuminance uniformity ratio between base case and case, simultaneously with recommended illuminance uniformity ratio on workspace (Steffy, 2002). Illuminance ratio, consist of maximum-to-minimum and average-to-minimum were used to quantify lighting uniformity. Illuminance uniformity on workspace should be 3:1 in average to minimum and 6:1 in maximum to minimum (Steffy, 2002).

Both cases had a high uniformity ratio on space. Illuminance uniformity ratio, average to a minimum, was 1.07:1 for both cases. Illuminance uniformity ratio, maximum to minimum, were 1.12:1 and 1.15:1 for base case and case, respectively. Illuminance uniformity ratio of HLP with an opening distribution of 6.6 m^2 and HLP with an opening distribution of 3.41 m^2 was in the range of recommended illuminance uniformity ratio on the workspace.

This results indicated that a single HLP running along the centerline of private office space and acted as a main source of daylight could evenly illuminate the space. HLP provided a uniform daylight, not only as a complement to side lighting [10, 11] but also as the main source of daylight inside the space. HLP in private office space could function as working space where a simple visual task is performed, such as computer-intensive offices.

The Effect of Opening Distribution Area on Daylight Distribution

The base case had a higher illuminance uniformity ratio than the case. This fact indicated that HLP with a larger opening distribution area distributed daylight more evenly than HLP with a smaller opening distribution area (Figure 10). Considering that both cases had a uniform daylight distribution, then HLP with an opening distribution of 3.41m^2 which had a higher daylight level than base case could be applied as the main source of daylight on office space.

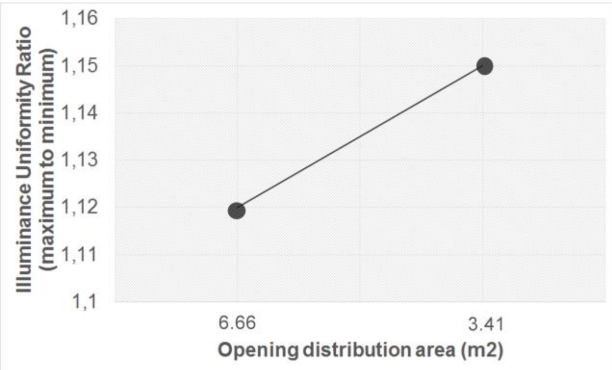


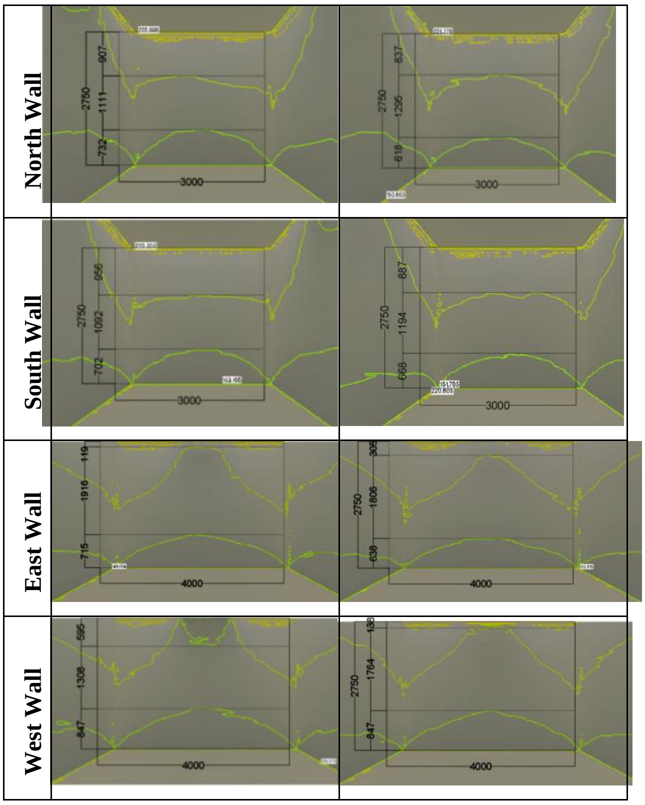
Figure 10 The effect of opening distribution area on illuminance uniformity ratio (maximum to minimum)

Table 3 describes illuminance distribution patterns of HLP inside office space. Both base case and case had a similar illuminance pattern, where all walls had a significant role in reflecting off daylight comes from opening distribution. Previous research by Beltran et al., 1997 showed that the back wall had a significant role in room illumination through HLP. The light came from opening distribution was reflected off the wall and improved work plane illuminance near to it. However, in this research other walls also have the same role as the back wall (West wall) in room illumination, especially the front wall (East wall). This was because the room proportion studied in this research is smaller, that were 3 m in width, 4 m in length and 2.75 m in height. With a small proportion of room, all walls had a role in reflecting daylight from opening distribution on the ceiling. The bright wall will make the room appear larger and more cheerful (Lechner, 2015).

The closer the distance of wall with opening distribution, the higher illuminance contour resulted. In this study, East and West wall which were perpendicular to the opening distribution had a strong role in reflecting daylight into space. The side walls (North and South walls) had a flatter illuminance contour, due to a greater distance from HLP's opening distribution (1-1.5 m).

Table 3. The pattern of HLP Illuminance Distribution on Interior wall

	Base case	Case



CONCLUSION

Modifying opening distribution area will change the reflection and distribution of daylight inside Horizontal Light Pipe. A reduction 50% of HLP's opening distribution area, which means reducing the area of transparent glass and adding the area of reflective specular material inside the pipe is proposed in this research. The current research has investigated the impact of HLP's opening distribution area on daylight performance at deep plan private office space in the topics.

A 50% reduction of HLP's opening distribution area, from 6.6 m^2 to 3.41 m^2 improved average Daylight Factor (DF) as much as 6.42%. The presence of highly specular material on opening distribution area contributed to the specular reflection of daylight before being transmitted to office space by a translucent glass.

In small room proportion (3 m in width, 4 m in length and 2.75 m in height), HLP along the centerline of room distributed daylight uniformly. A lower illuminance uniformity ratio but still meet the recommended illuminance uniformity ratio on workspace was resulted by a smaller HLP's opening distribution area. Considering the improvement of daylight level and high uniformity ratio resulted, HLP with a smaller opening distribution area can be applied as the main source of daylight on deep-plan office spaces.

Further research and development of HLP to meet the requirement for a more complex visual task in deep plan office space is needed. Several modifications of HLP's opening distribution element can be investigated, including the addition of reflectors and louvers.

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