SEMARAK ILMU PUBLISHING

Journal of Advanced Research in Applied Sciences and Engineering Technology

Journal homepage:
https://semarakilmu.com.my/journals/index.php/applied_sciences_eng_tech/index
ISSN: 2462-1943

Efficiency Analysis of a Passive Daylighting System Based on Northern Malaysia's Climate

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ARTICLE INFO

Article history:
Received 13 October 2023
Received in revised form 11 April 2024
Accepted 26 April 2024
Available online 25 May 2024

Keywords:
Daylighting; Light pipe system; Illuminance measurement; Passive daylighting; Lighting analysis

ABSTRACT

Daylighting design strategy is important in order to have adequate lighting source in a room and necessary to decrease energy consumption for artificial lighting. Passive daylighting system utilizes daylight by collecting, reflecting and diffusing the natural light throughout a given area. The purpose for this study is to monitor, compare and analyse an optimum light pipe system design that can scatter daylight into a room based on three case studies. Lighting analysis was conducted using Autodesk 3ds Max Design software throughout the project based on the actual geographical parameters of Universiti Malaysia Perlis, Malaysia and also using the real sun azimuth on working hours. The results were compared according to the respective designs in order to observe the maximum internal illuminance and the average internal illuminance. The results show that the straight geometry with low aspect ratio produces the highest interior light intensity among other light pipe systems and the average internal illuminance values in the room was able to reach the minimum requirement of a small room which is 200 – 500 lux.

1. Introduction

Daylighting is an approach to illuminate building interiors with natural light to create pleasant visual environment and to save energy [1-4]. Sufficient daylighting reduces energy consumption and also makes a house, office and other building sectors livelier and healthier place for working or living and even in healthcare facilities [5-7]. In Malaysia, application of daylighting by illumination dome and large windows are widely used as an alternative to conventional lighting systems. However, typical domes or large windows such as in commercial buildings may decrease the level of comfort inside the building as the heat from the sunlight may increase the temperature inside the building. Thus, utilizing passive tubular daylighting system can be a solution for both domestic and commercial

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https://doi.org/10.37934/araset.46.1.107117

buildings. The concept of daylighting system is started with the sunlight being collected by the top of the dome and travels down into highly reflective pipe through multiple specular reflections and then reaches the diffuser level where it is dispersed throughout a given area [8].

The increase of demands for electrical energy is a significant issue with the rise of standard living in society, urbanization, industrialization, and transport development. The consumption of electric lighting is a concern by the level of usage in residential buildings at 25.3%, shopping complexes 51.9% and offices 42.5% [9-11]. Thus, increasing the use of natural daylighting for lighting purposes in buildings can offer major savings in energy consumption, improves internal environment, and also replaces electric lamps during daytime [10,12,13].

The main aim of this paper is to focus on designing an optimum light pipe based on the efficiency of geometry and its' aspect ratio. The design of light pipe structure plays an important role in daylighting system as the reflected light that emitted from the light pipe to the diffuser can transform a dark space into space that is bright and full of natural light [14-16]. The recommended light intensity for offices, classes, libraries, show rooms and laboratories is 200 ~ 500 lux [12,13,17].

2. Potential of Daylighting System in Malaysia

Malaysia is a tropical country near the equator with hot humid tropics, steady temperature, high humidity, and copious rainfall. The characteristics for Malaysia's climate allowed and enable the usage of solar resources to be utilized via daylighting system. Thus, the collection of daylight data is crucial to be considered in designing buildings using daylight [1,12]. The quality and quantity of external illuminance in a particular location is always considered primarily in many previous studies [12-18]. The location for external illuminance data collection for this study is at Campus Pauh Putra, Universiti Malaysia Perlis (latitude, 6.458575° and longitude, 100.346311°) to validate the capacity and pattern for northern region of Malaysia's climate. In order to get precise and consistent data, the average external illuminance data is recorded for a year from 8.00am until 5.00pm during working hours using a light meter as shown in Figure 1.

Fig. 1. Lux meter HS1010

From Figure 2, it shows that each month the maximum levels vary with the maximum average external illuminance is 98,153 lux and the minimum average external illuminance with 35,997 lux. This proved that the outdoor illuminance at Campus Pauh Putra, Perlis is in line with the minimum external illuminance value reported by previous researchers depicted in literature [1] and [12] with the lowest external illuminance below 20,000 lux. Therefore, the sunlight can provide sufficient light intensity during daytime to illuminate any building sectors using daylighting system, particularly in the test region which are at Perlis, Malaysia.

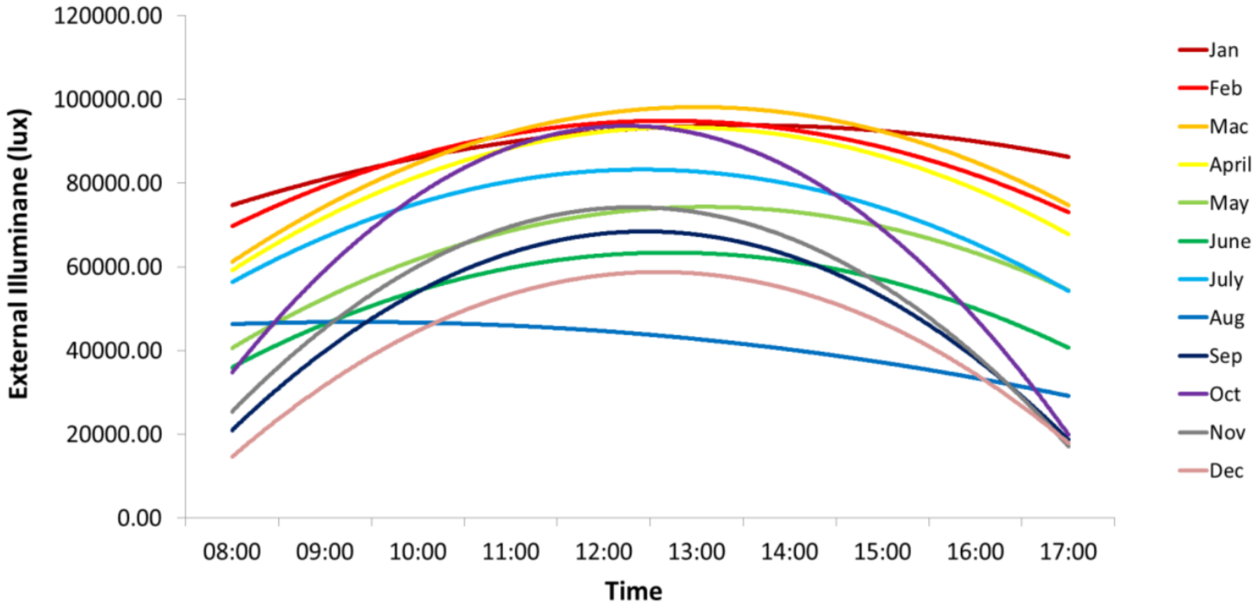
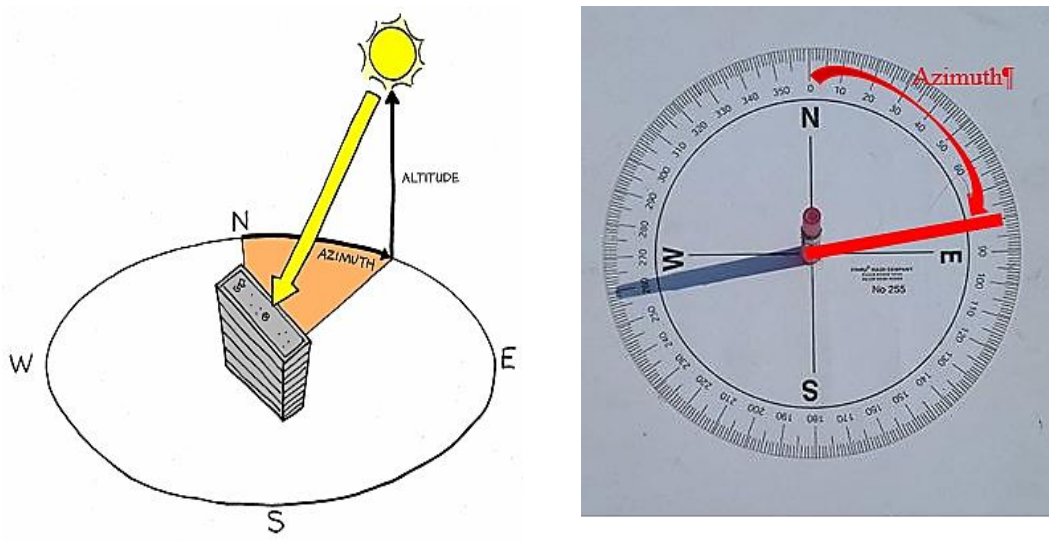


Fig. 2. Average external illuminance against time over a year

In addition, solar angle or altitude data have also been recorded. A compass bearing board was used to measure solar angles as shown in Figure 3. The solar angle was calculated by using Pythagorean Theorem equation as shown in Eq. (1), which is the inverse tangent of length of shadow formed by object over the original length of object.



(a) (b)

Fig. 3. Measurement of solar angle (altitude); (a) theoretical, and (b) experimental

$$\tan\theta = \frac{l_o}{l_x} \quad (1)$$

where, Θ = sun inclination angle, l_o = Actual length of the object, and l_x = Length of shadow formed by object.

The average solar angle for each month is shown in Figure 4. The highest maximum solar angle occurred in the month of September with 80.8° at 1pm, while the lowest maximum solar angle was recorded in the month of November with 62.9° at 1pm. The minimum solar angle is expected at 8.00am and 5.00pm.

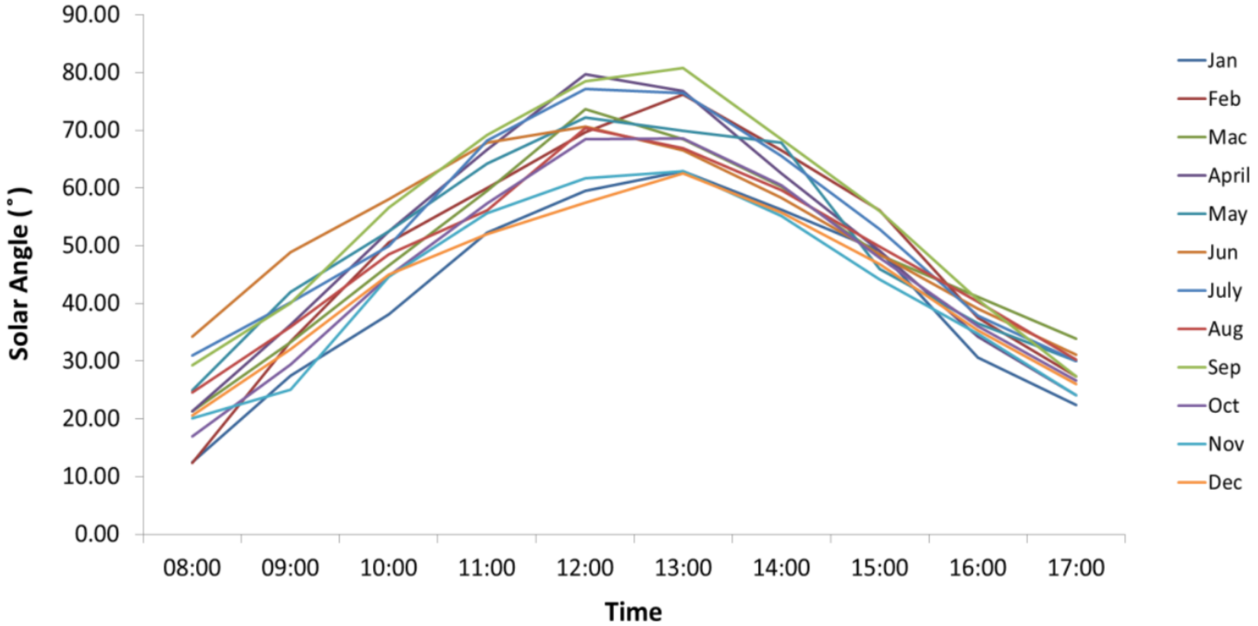


Fig. 4. Average solar angle against time over a year

3. Experimental Setup

The test room was prepared as depicted in Figure 5. The dimension of the test room is 3m × 3m × 2.5m (length × width × height). This dimension was selected as a medium to resemble a lecturer room at Universiti Malaysia Perlis (UniMAP) campus as the analysis is focused on lighting a small-scaled room and the main part included in the room are wall, floor, and ceiling. The experiments were carried out to simulate the internal illuminance of the daylighting system and the comparative and efficiency study was conducted based on the results of the different light pipes configuration.

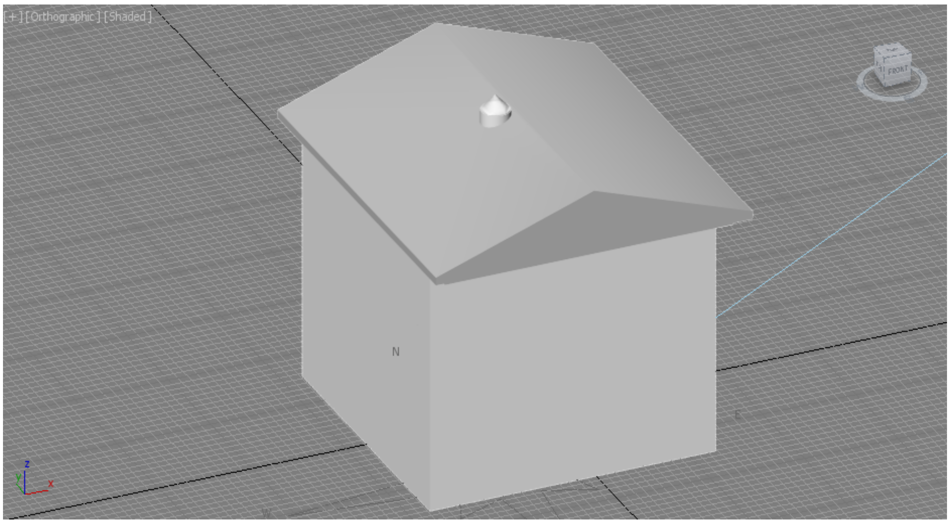


Fig. 5. Model of test room installed with straight light pipe in 3ds Max Design

There are three passive daylighting systems that were designed based on Monodraught sun pipes. Each system has a different design in terms of size and geometry of the light pipe as shown in Figure 6.

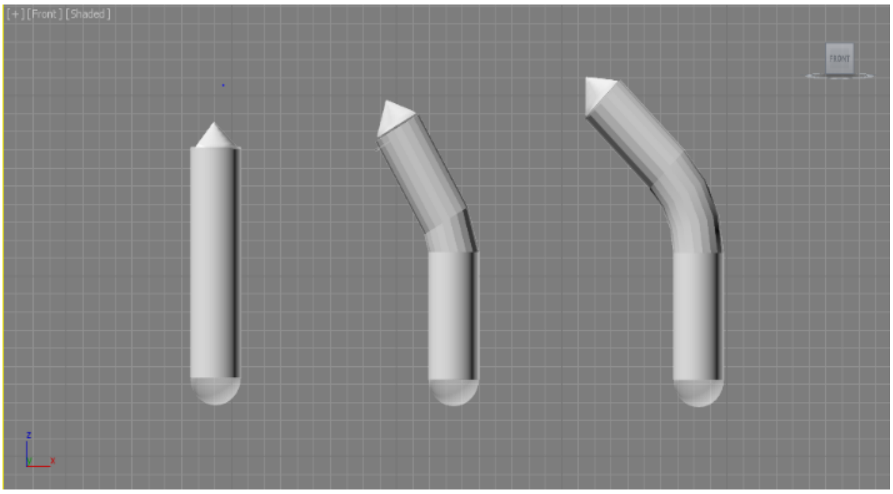


Fig. 6. Three light pipe configurations with diameter of 30cm; (a) Straight, (b) 30° and (c) 45° light pipes

Other parameters such as material of light pipe, thickness of light pipe, dome and diffuser remain constant as tabulated in Table 1. Furthermore, a variable named aspect ratio (ratio of length/diameter) is used in order to investigate the relationship of length and diameter over light transmittance. The distance between the diffuser and the floor is fixed throughout the lighting analysis with 210 cm. The light pipe was developed with 98% of reflectance in favour of the actual Monodraught sun pipe's attributes as a mirrored surface light pipe.

Table 1
Parameters of the Case Study

Light pipe	Case Study 1			Case Study 2			Case Study 3
	Straight (0º)			30º			45º
Light Pipe Diameter	25cm	30cm	35cm	25cm	30cm	35cm	30 cm
Light Pipe Length	120cm			120cm			120cm
Aspect Ratio	4.8:1	4:1	3.4:1	4.8:1	4:1	3.4:1	4:1
Light pipe Material	Aluminium			Aluminium			Aluminium
Light Pipe Thickness	3mm			3mm			3mm
Dome Type	5-leaf Diamond			5-leaf Diamond			5-leaf Diamond
Diffuser Type	Opal			Opal			opal

The analysis of this study comprises of three case studies to evaluate the contrast of daylighting system performance through variation of sizes and geometries using Autodesk 3ds Max Design software. The reliability of this software was verified by the previous researchers in the study of daylighting in various buildings [19-22].

The parameter of every case study is tabulated in Table 1 and the actual external illuminance data were used to simulate the internal illuminance inside the room. Case study 1 and 2 consist of three different sets of light pipe diameters which are 25 cm, 30 cm and 35 cm. The case study 3 on the other hand consists of only one testing parameter. The relationship between the aspect ratio with the light transmittance is studied and analysed to determine the optimum dimension for the design of light pipe.

4. Results and Discussion

The light intensity simulation is analysed using Autodesk 3ds Max Design software. The analysis shows the light intensity level surrounding the room and was made to evaluate the depth of daylight penetration through selected commercial light pipes. Table 2 tabulated the measurement of the illuminance and later plotted as shown in Figure 7.

Table 2
Internal and External Illuminance for each daylighting system

Time	Internal Illuminance (lux)							External Illuminance (lux)
	Monodraught							
	0° light pipe			30° light pipe			45° light pipe	
	25 cm	30 cm	35 cm	25 cm	30 cm	35 cm		
8:00	195	205	216	186	190	200	181	59960
9:00	207	218	229	197	202	212	192	75720
10:00	278	292	307	265	271	285	258	86560
11:00	356	374	393	339	347	366	330	91900
12:00	665	699	734	626	642	676	609	95660
13:00	745	784	823	702	720	757	683	96580
14:00	820	862	905	764	784	825	744	95060
15:00	676	711	745	644	658	694	626	93520
16:00	341	359	375	324	330	349	315	89420
17:00	229	241	251	218	221	235	212	71900
Average	451	475	498	427	437	460	415	85628

The highest lux value recorded around 1.00pm until 2.00pm for all seven light pipe configurations. These measurements concur with the fact that the sun emits the highest natural light and is closer to solar zenith angle within this time. The graph indicates that the 0° light pipes transmit higher illuminance levels than the 30° and 45° light pipes at the level of 210 cm underneath the diffuser. Throughout each interval of working hours, the 0° light pipe with 35 cm dominantly shows the highest average internal illuminance with 498 lux. The second highest average lux value is the 0° light pipe with 30 cm diameter yield 475 lux followed by the 30° light pipe with 35 cm for 460 lux. The lowest average lux value is 415 lux from the 45° light pipe. Based on the arrangement of results, the straight light pipes produce the highest amount of average internal illuminance due to the characteristics of the geometry and largest aspect ratio in terms of length and diameter.

For straight light pipes, multiple specular reflections occurred inside the light pipe is higher compared to bending geometries as the principal section has minimum incident angle for rays which satisfy the total internal reflection condition. A relationship linking the aspect ratio of the light pipe (ratio of length/diameter) with the light collected and transmitted at the diffuser level is critical in order to design a high efficacy daylighting system. A low aspect ratio will expose and be subjected to higher number of reflections inside the light pipe and hence, the light reaching the diffuser will be more dispersed [23,24].

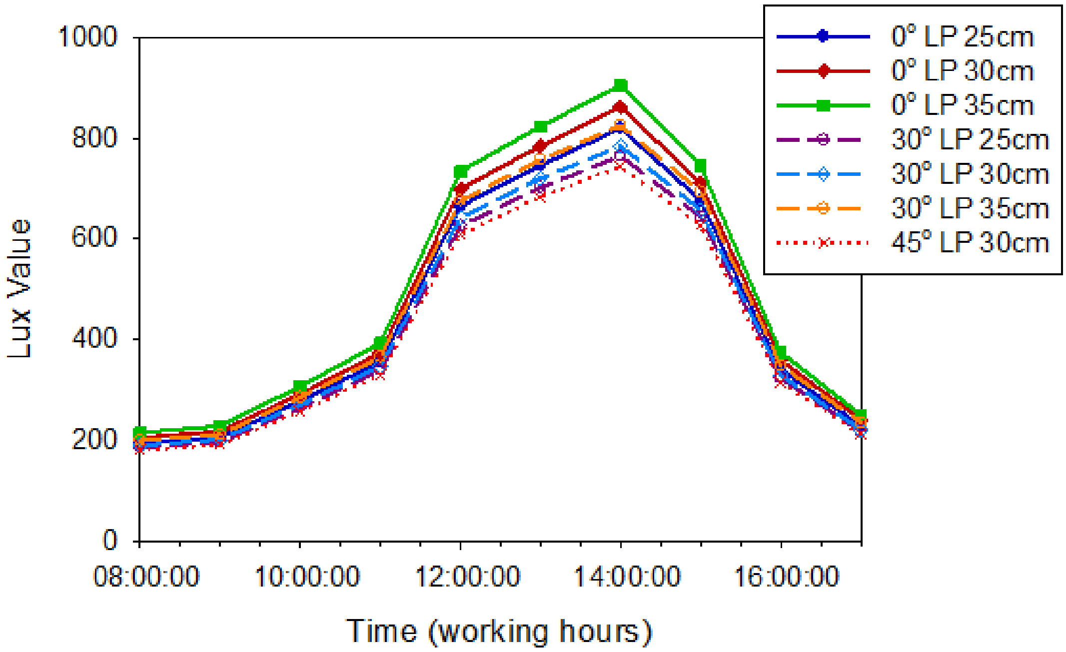
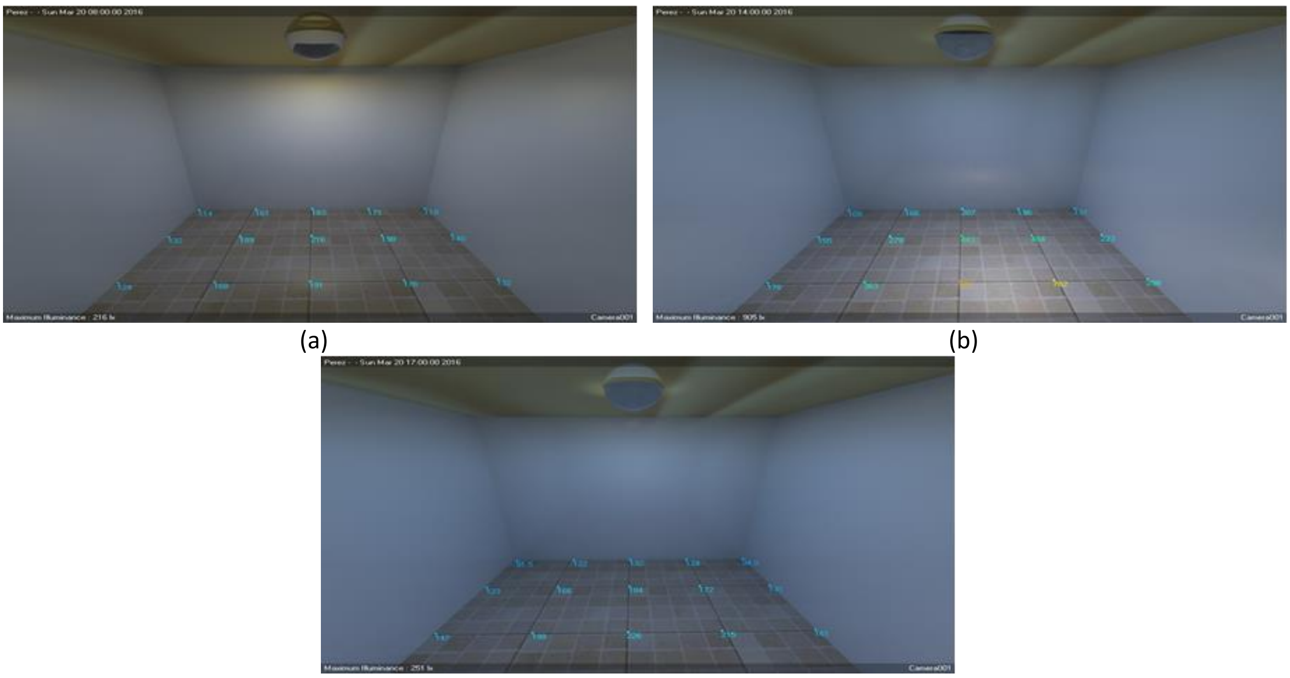


Fig. 7. Internal Illuminance distribution against time for different light pipes

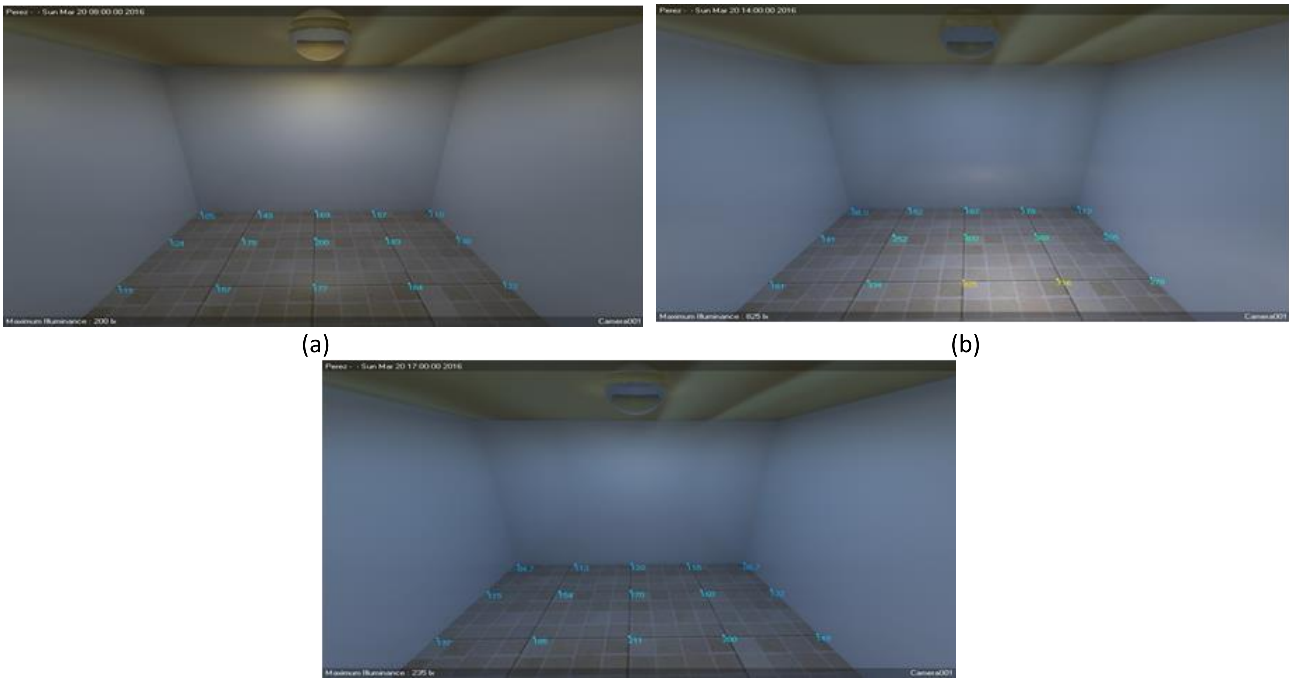
Based on the measurement in Table 2 and the illuminance distribution in Figure 8, the lux value for the 0° light pipe with 35 cm starts from 216 lux as the minimum internal illuminance level at 8.00am then reached the maximum internal illuminance on 14.00am with 905 lux and gradually declined to 251 lux at 5.00pm. Figure 8(b) illustrates that the maximum lux value that is able to penetrate into the interior of the test room is recorded and located in the middle of the room with 905 lux.



(a) (b) (c)

Fig. 8. Maximum internal illuminance for 0° light pipe, 35cm length. (a) 216 lux at 8.00am; (b) 905 lux at 2.00pm; (c) 251 lux at 5.00pm

Figure 9 alternatively shows the 30° light pipe with 35 cm produces the minimum illuminance level with 200 lux at 8.00am, steadily increased to 825 lux as the maximum illuminance level at 2.00pm then finally dropped to 235 lux at 5.00pm with respect to the measurement tabulated in Table 2.



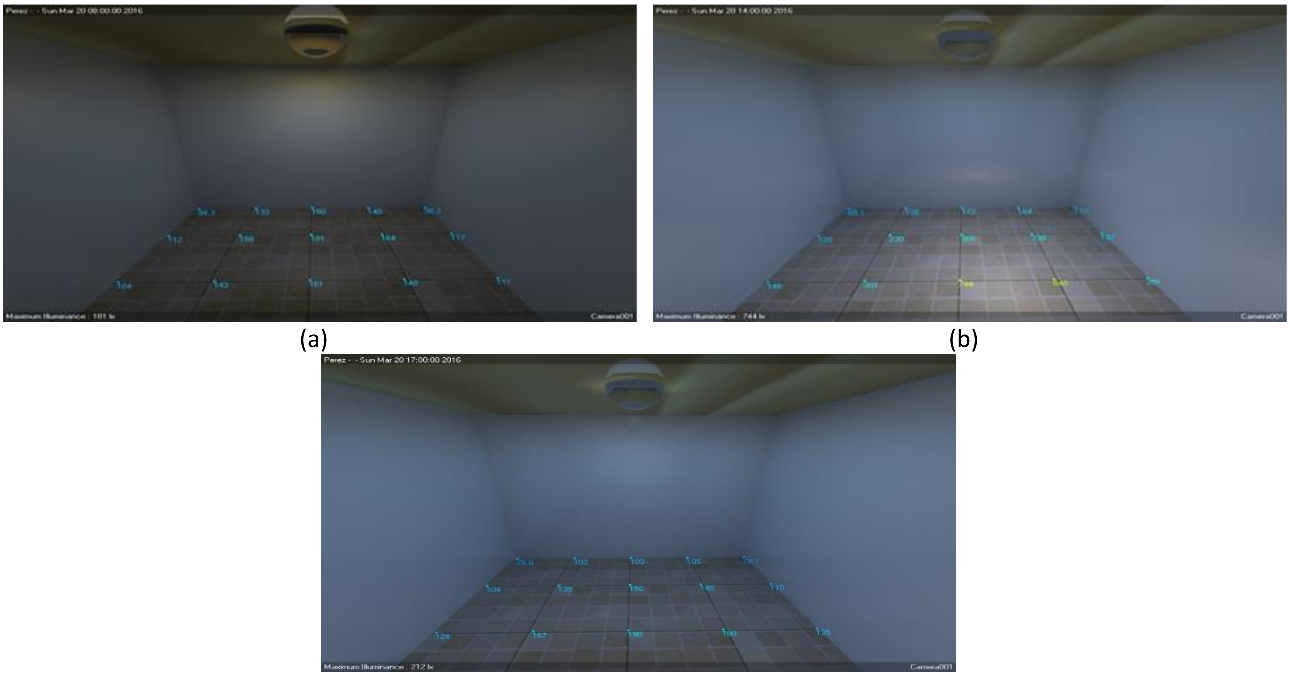
(a) (b)

(c)

Fig. 9. Maximum internal illuminance for 30° light pipe, 35cm length. (a) 200 lux at 8.00am; (b) 825 lux at 2.00pm; (c) 235 lux at 5.00pm

Figure 10 on the other hand demonstrated the lowest bell-shaped curve occurred on the 45° light pipe with 30cm. The initial illuminance level at 8.00am is 181 lux, then extends to 744 lux on 2.00pm and finally decreases to 212 lux at 5.00pm.

Figures 8, 9 and 10 show the selected interior scenes of light pipe installed inside a test room for the 0° light pipe with 35 cm in case study 1, the 30° light pipe with 35 cm in case study 2 and the 45° light pipe with 30cm in case study 3. Most of the lux value distributed around the room is more than 200 lux. This indicates that the light intensity is sufficient throughout the room and fulfils the illumination level recommendation.



(a) (b) (c)

Fig. 10. Maximum internal illuminance for 45° light pipe, 30cm length (a) 181 lux at 8.00am; (b) 744 lux at 2.00pm; (c) 212 lux at 5.00pm

5. Conclusions

This study has conducted a parametric design analysis for passive light pipe systems to naturally illuminate a room or building sectors. The study shows that the external illuminance in Perlis, Malaysia is suitable for the utilization of light pipe system as the external illuminance extensively influence the performance of light pipe system during working hours. Within a range between 180 lux to 1,000 lux over a period from 8.00am until 5.00pm, this system was able to maintain the internal illuminance level for most of the normal working hours for any activities or works. From the results, it can be concluded that the light pipe with longer length, and straight geometry is the optimum design for a passive daylighting system.

However, this study has not considered the effects of different design of dome and diffuser on the daylighting system. Therefore, further analysis of these components can be conducted in order to evaluate the complete daylighting system. Moreover, the results obtained in this study signify that the performance of daylighting system via photometric simulations needs further validation with experimental data in order to ensure the accuracy for design purposes.

Further works can also be conducted for the integration with artificial light sources in order to manipulate and suffice the internal illuminance level during overcast or rainy seasons. In conclusion, abound of benefits is gained via daylighting system by minimizing the usage of electrical consumption and has the potential to be widely used in Malaysian buildings.

Acknowledgement
The author would like to acknowledge the support from the Research Acculturation Grant Scheme (RAGS) under a grant number of RAGS/1/2014/TK06/UNIMAP/02/1 from the Ministry of Higher Education Malaysia.

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