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Investigating the Thermal and Lighting Performance of Light Pipes for Sunny and Cloudy Conditions in Insular Tropical Climate

Dudley Anthony Williams and Jean-Francois Marc Dorville
Department of Physics, Faculty of Science and Technology, University of the West Indies, Mona Campus, Mona 1876, Jamaica

Abstract: Tubular light pipes (i.e., solar tubes) are modern daylighting devices, which are designed to let confined interior spaces benefit from natural lighting. In tropical country, the use of sunlight for lighting is a major concern due to the heat associated with sunlight, which has the potential to increase the cost of cooling, thereby reducing the energy savings from the reduction in lighting load. To investigate the thermal and lighting performance of light pipes, a case study for a seminar room, in which light pipes are installed, is presented. Temperatures for the solar tube (dome and diffuser), window and room were monitored continuously for 24 h periods. Results from the study indicate that the diffuser was on average 6.68 °C higher than room temperature on a clear day between 7:00 a.m. and 4:00 p.m., while dome temperature was on average 4.45 °C higher than diffuser's temperature during the same period. This large thermal gradient in the day between dome, diffuser and room can significantly increase the cost of maintaining thermal comfort of 25 °C, in the room. Another finding was the phenomenon of light pipes acting as a heat pumping the night, because it extracts heat from the room during the night between 7:00 p.m. and 4:00 a.m. This occurred because dome temperature is always smaller than diffuser and room temperature in the night. Therefore, for energy savings to be realized from light pipes, thermal performance must be taken into consideration in the analysis of energy savings from light pipes.

Key words: Thermal, tubular light pipe, solar tube.

1. Introduction

LPs (light pipes) are becoming increasingly popular as daylighting devices because of its ability to transport sunlight to places that are physically impossible to be lit by windows and its predecessor, the normal skylights. LP unlike its predecessors consists of a dome (located on the roof) that captures light and a diffuser (located in the ceiling) that spreads light into the room, both being linked by a light guide that is able to transport sunlight into the core of buildings. These characteristics give LP the possibility to reduce daytime electric lighting for core spaces by 100%. However, like its predecessors, LP transfers heat along with the light it admits into rooms [1], which is an undesired effect for tropical countries or during summer in temperate countries. This paper presents a case study on the thermal and lighting performance of light pipe under cloudy and sunny conditions in the tropical climate of Jamaica.

2. Background

Since the invention of LP, there have been various studies on its lighting performance, and limited studies on its thermal performance [2-5]. In 2004, Jenkins and Muneer [4] described six different studies that created methods of predicting the lighting level expected from LP. However, the studies listed did not shed light on the thermal output of the system. In 2000, Oakley et al. [6] stated that LP transmits less heat than a window into a room, but did not explore further. No empirical data or specification on the type of window or type of solar tube used in comparison was given to justify their conclusion. Their limited focus on the thermal aspect

Corresponding author: Dudley Anthony Williams, master student, research fields: renewable energy and lighting. E-mail: dudley.williams.uwi@gmail.com.

was not surprising because the study was done in the United Kingdom, a country with a colder climate. The added heat would reduce the electric heating needs of the building through passive heating. However, in a tropical country like Jamaica, passive heating is not practiced, but rather cooling of buildings. Therefore, any heat added to the room increases the power consumption of the room because additional cooling will be required from fans or air conditioning units to maintain thermal comfort. Wu and Yue [1] provided much more information on the thermal aspect of LP. Wu and Yue [1] also explored the lighting component of LP and provided data on the temperature of diffuser and dome for two sunny days in Beijing. They observed that temperature of diffuser was higher than roof's temperature, and concluded that light pipe added heat to the gymnasium [1]. Hien and Chirarattananon [7] in 2007 explored the heat gain from a horizontal light pipes in India. They reported that the cost of cooling increased with the installation of solar tube.

Since the thermal ingress from solar tube is an undesired effect, one would think that a lot of studies would have been done to mitigate it; but this is not the case. As an illustration, there are studies on the thermal aspect of LP for natural ventilation because of the temperature gradient along its side [8] and on how LP affects the thermal insulation of roofs they are installed in [9]. But no study so far has developed any equation to predict the temperature increase cause by LP inside rooms or how the temperature of LP varies with solar radiation received. More progress can be seen on the lighting aspect of LP through the various equations [2] and software developed to better understand it lighting performance (skyVision [6] and Holigilm [10]).

However, if light pipes are to become viable options for reducing energy consumption of buildings in tropical climates that have abundant sunlight all year long, the thermal aspect must be taken into consideration. For instance, the addition or subtraction of heat from the room will dictate how much cooling is required to maintain thermal comfort within the room. Focus must therefore be placed on the overall energy savings of LP, which consist of the increased cost of cooling and the reduction of lighting consumption of the room.

3. Experimental Setup

The monitored room used in this experiment was located on the first floor of the Department of Physics, U.W.I Mona (18.010 N, 76.750 W, 600 m elevation). The overall structure of the building is concrete. The dimensions and composites of the room can be seen in Fig. 1. The area of the seminar room is 56 m^2, with a width of 7.44 m, a length of 7.55 m, and an average

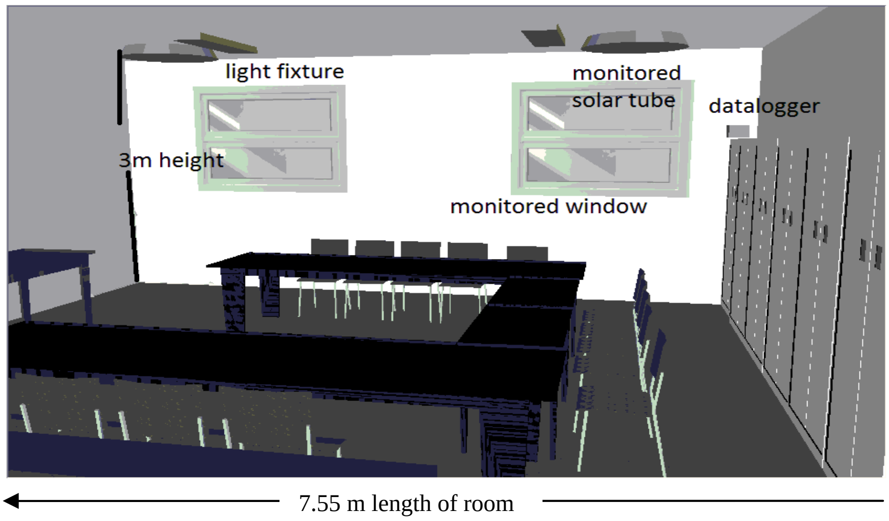

Fig. 1 Layout of monitoring room (Physics UWI, Mona seminar room).

height of 3 m. The thicknesses of the walls are 0.135 m. The western, eastern and southern walls are painted ash grey, while the northern wall is painted lightblue. The interior of the roof is painted white. This room was chosen because there are no permanent internal heat sources; however, there are temporary internal sources that add heat into the room such as body temperature, computers and projectors that are present during meetings.

3.1 Lighting Technologies in Experimental Room

Light pipes: There are four 750 DS-0 HVHZ kits with eight flashing, 24" tube and an Optiview diffuser ST installed in the Seminar Room, circular protrusions in the ceiling (Fig. 1). Each has a 750 DDS daylight dimmer, which is controlled by one ST dimmer switch. The surface area of each diffuser is 0.204 m^2 and is extended 0.23 m from the ceiling into the room [11].

The Seminar Room has four single pane glass windows with metal frames painted grey on the eastern and on the western side. There are two windows on each side. The windows on the eastern side are identical in dimensions 1.94 m × 1.48 m and height above floor. All windows have a light colored Venetian blind in front of them (Fig. 2).

There are four lighting luminaires, each equipped with two fluorescent lamps (32 W, T8 tubes) and electronic ballast, the location of which is depicted in Fig. 1.

3.2 Description of Days

The thermal results presented hereafter were taken from Thursday February 13 to Sunday February 16, 2014. Thursday February 13 started with a sunny morning between 7:00 a.m. and 10:00 a.m., followed by 2 h of frequent cloud cover (solar radiation fluctuated between 100 lux and 800 lux). At midday, the frequency of cloud cover reduced and eventually cleared at 2:00 p.m. This state remained for the rest the day until the sun set, which occurred at around at 6:00 a.m. (Fig. 4). Sunday February 16, 2014 was mostly overcast with various spikes of high solar radiation peaking at 1,000 Wm^{-2} (Fig. 5). For a summary of weather data irradiance and ambient temperature and temperature collected for February 2014 in Table 1.

4. Experimental Configuration

4.1 Temperature Measurement

RTD (resistor temperature detector) sensors were used to take temperature readings. Temperature was taken for three points in the room: on the LP, on the glass of one of the eastern facing window, and on the glass of the bookcase within the room. Readings were collected at 5 min intervals using the Omega 320 data logger. A second data set was taken from a Vantage pro2 weather station on the roof of the physics building which included outdoor ambient temperature and irradiance at 1 min intervals, since 2011. The complete data sets were analyzed using the Python software.

4.2 Lighting Measurement

A two-day experiment was conducted to measure the luminous flux being produced by the LP and the electric light bulbs to ascertain their performance under different weather conditions. The configurations of the experiment are as follows: firstly, lighting levels were measured in the room with lights off, and solar-tubes and BC (blinds closed). This was done to capture how dark the room was without additional light. Then all four solar-tubes were opened with BC (SOBC). LPs were fully closed then electric light turned on (EOBC). Measurements were taken on a work-plane of 1 m height. Data for each configuration were taken at 2 min intervals using an EXTECH 407026 lux meter (Fig. 3).

4.3 Limitations of Measurements

Due to the nature of the room, the A/C unit was used whenever meetings were held. This period is denoted by the depression in room temperature in Fig. 4. Also, because of the high luminous intensity of the LP, the degree to which it was opened varied based on the needs of the occupants in the room.

Fig. 2 Experimental room displaying two of the four light pipes under sunny conditions and the light distribution.

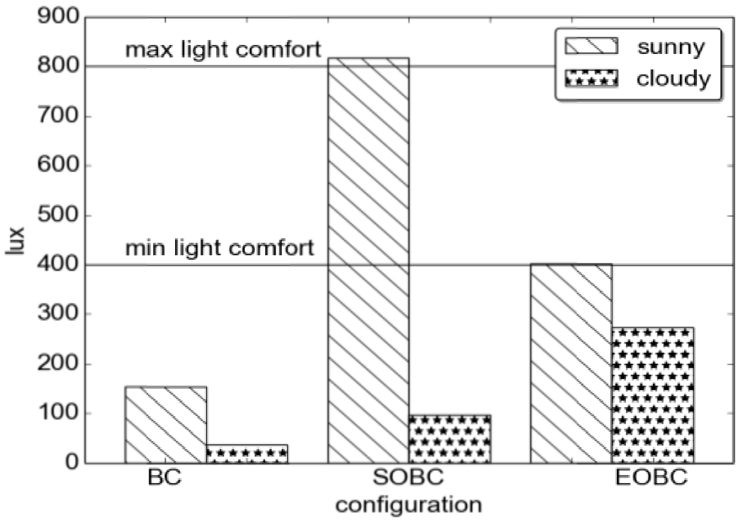

Fig. 3 Illuminance (lux) levels for different configurations for sunny and cloudy day inside the experimental room.

5. Results

5.1 Lighting Results

Lighting levels for LPs, on a sunny day, were more than double that of the electric lighting system. However, the reverse occurred under cloudy condition, where electric lighting outperformed LP. From these observations, it is clear that LP can provide sufficient lighting in the day, for offices (recommended lighting level is 300-500 lux) in tropical climates under clear skies. (Fig. 3)

5.2 Thermal Results

Fig. 4 shows that diffuser and dome temperature varies similarly in relation to solar radiation. Dome temperature, however, shows a greater relationship with solar radiation than diffuser temperature. Dome temperature peaks when solar radiation peaks between 12:00 p.m. and 1:00 p.m. (Fig. 4), while diffuser temperature peaks in the evening when the sun is receding below the horizon, about 5:00 a.m. Dome temperature varied, for a sunny day, between 22 °C and 45 °C in February. However, diffuser temperature showed a fluctuation between 28 °C and 38 °C. Diffuser shows an almost linear relation between 9:00 a.m. and 3:00 p.m., showing that its temperature is not dependent only on radiation but on other factors. These factors could include the temperature of the concrete that surrounds the tube section of the solar tube, or the temperature of the air column trapped in the tube. It could also be a combination of both factors.

Fig. 5 which represents a cloudy day further confirms that the temperature of the dome has a stronger correlation with solar radiation received than

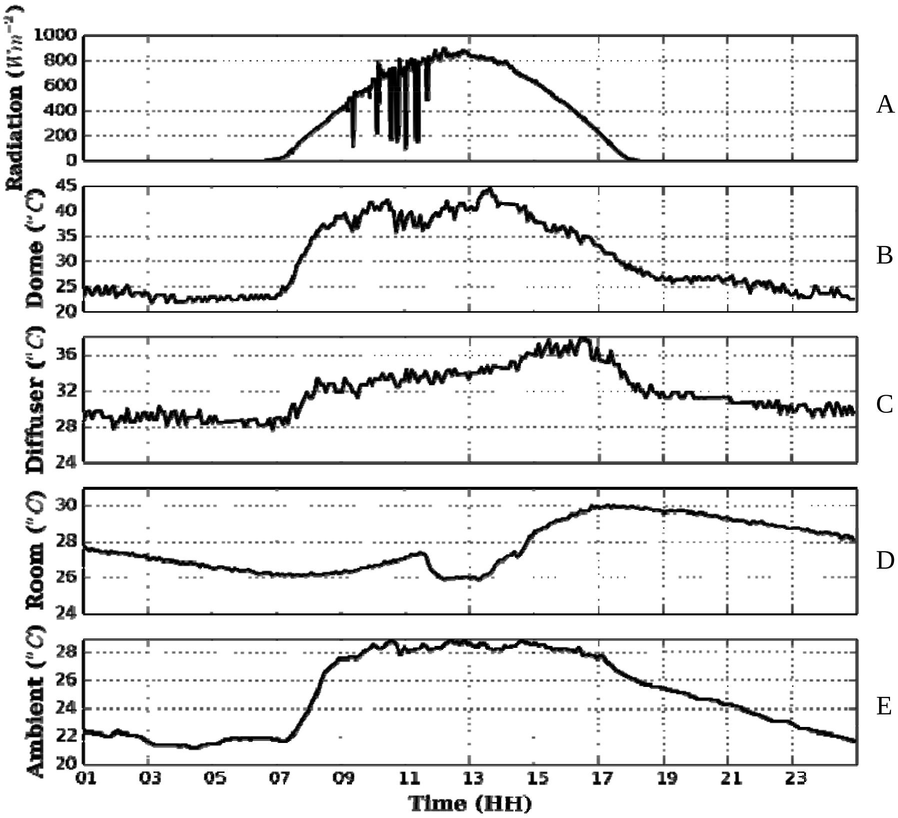

Fig. 4 Five time series graphs: (A) radiation time series; graphs (B, C, D, E) represent dome, diffuser, room and ambient temperature time series respectively for February 13, 2014, a sunny day.

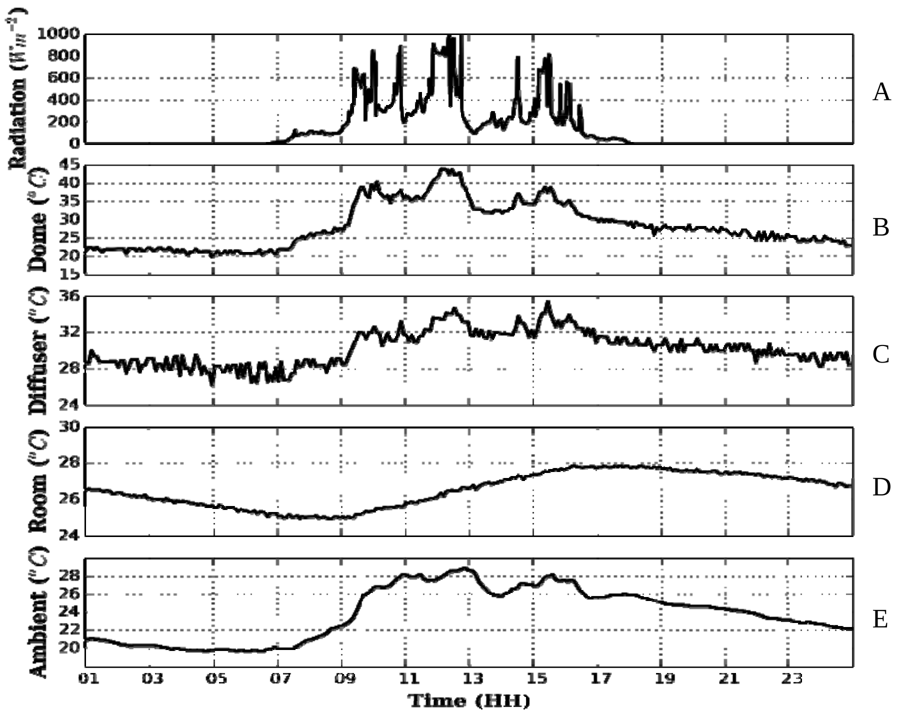

Fig. 5 Five time series graphs: (A) radiation time series; graphs (B, C, D, E) represent dome, diffuser, room and ambient temperature time series respectively for February 16, 2014, a cloudy day.

Table 1 Summary of data collected for 12 days of February 2014.

	Dome (°C)	Diffuser (°C)	Room (°C)	Ambient (°C)	Radiation (Wm^{-2})
Monthly maximum	54.75	43.18	33.72	33.4	1,202
Monthly average	30.44	32.37	28.74	25.85	382

Table 2 Summary for the analysis of temperature data for dome-diffuser, diffuser-room, extreme dome-diffuser and diffuser-room, and time extreme occurred.

February 13, 2014, a sunny day						
Time period	Average dome-diffuser (°C)	Max dome-diffuser (°C)	Time max occurred	Average diffuser-room (°C)	Max diffuser-room (°C)	Time max occurred
7:00 a.m.-4:00 p.m.	4.45	10.51	1:36 p.m.	6.68	8.77	1:21 p.m.
7:00 p.m.-4:00 a.m.	-5.34	-7.61	4:06 a.m.	1.7	0.39	1:56 a.m.
February 16, 2014, a cloudy day						
7:00 a.m.-4:00 p.m.	2.43	10.52	12:06 p.m.	5.22	8.15	12:36 p.m.
7:00 p.m.-4:00 a.m.	-4.93	-8.29	3:46 a.m.	2.58	1.23	11:56 p.m.

diffuser temperature. The fluctuations in irradiance were greater reflected with the dome temperature than diffuser temperature. Noteworthy, the fact that diffuser temperature was higher than dome temperature for most of the day except between the hours of 7:00 a.m. and 4:00 p.m., a period where maximum solar radiation is received. Dome temperature is higher than diffuser temperature for only 10 h of the day. This means that during this period, there is a thermal ingress of heat in the direction of the diffuser, which ultimately enters the room. However, when the sun's solar angle begins to decrease, starting at 3:30 p.m., the direction of temperature gradient changes as dome temperature is now less than diffuser's temperature. From the experiment, it is hypothesized that the solar tube extracts more heat from the room than it adds to it. To investigate this peculiar behaviour of the solar tube, Table 2 was created to give an idea of the temperature difference for diffuser and dome and for diffuser and room. When the temperature data were analyzed, it was noticed that for both days, maximum temperature difference for sunny and cloudy day was 10.5 °C, which further proof the strong co-relation that dome has with irradiance received. When the average of the temperature difference was taken for hours between 7:00 a.m. and 4:00 p.m., and between 7:00 p.m. and 4:00 a.m., it was noticed that dome temperature was greater than diffuser temperature during the first period; but in the later period, diffuser temperature was greater than dome. The negative sign found in Table 2 indicates that diffuser temperature was higher than dome temperature during this period. When the average temperature for the two periods was compared, diffuser temperature was 16.6% higher than dome temperature for the sunny day. This seems to indicate that if raw data were entered in the equation for conduction (Eq. (1)), then the solar tube would have extracted more heat from the room than it added during the day. On the cloudy day presented, this phenomenon was more pronounced where the summation of the temperature difference in the day was 2.43 °C, indicating that dome temperature was higher in the day. However, in the night a -4.93 °C was calculated which indicated that diffuser temperature was significantly higher than dome temperature during the night. Since heat flows from hot to cold, it can be hypothesized that the solar tube pumped twice as much heat from the room on the cloudy day than on the sunny day observed. Further research needs to be done to ascertain if this effect is beneficial to building owners in terms of energy consumption.

$$\mathbf{Q} = \frac{\mathbf{kA}(\boldsymbol{T}_{\mathbf{hot}} - \boldsymbol{T}_{\mathbf{cold}})}{\boldsymbol{d}} \quad (1)$$

where, **Q**—heat conducted; **k**—thermal conductivity; **A**—area; T_{hot} and T_{cold}—temperature of both objects, *d*—thickness between objects.

Figs. 4 and 5 show that ambient temperature varies differently from room temperature. Outdoor temperature varies analogously with radiation received. Ambient temperature variation resembled a bell curve, while room temperature variation resembled a sine wave. From both graphs, room temperature had a “trough” between 7:00 a.m. and 9:00 a.m. and a “crest” between 5:00 p.m. and 7:00 p.m. Outdoor temperature showed strong correlation with radiation between 7:00 a.m. and 9:00 a.m. According to Fig. 4(E), ambient temperature increased by 4 °C during this period, which represented its greatest increase, but started to decrease at 5:00 p.m., when room temperature reached its apex. The shape of room temperature time series graph does not fluctuate with changes in weather conditions. How hot the room gets, however, is directly related to radiation received. The maximum room temperature for February 13, a sunny day, was 30 °C, which was 2 °C higher than on February 16, a cloudy day.

From Figs. 4 and 5, it was noticed that room and diffuser temperature peaked in the late evening when the sun is setting. This agrees with conclusion drawn by Pollard, Driscoll and Pinder [12], which describes it as being a delayed heating effect of solar radiation on indoor temperature, better termed as thermal inertia.

6. Conclusions

Tubular light pipes installed in tropical climates add substantial amount of heat, in the day, to rooms it is installed in. This amount if heat should not be ignored as it will increase cost of maintaining roof comfort, especially in rooms that are air conditioned. Therefore, mitigation strategies are necessary to realize overall energy savings during operation within tropical climates. This study observed that for a clear sunny day, difference between dome and diffuser temperature between 7:00 a.m. and 4:00 p.m. was 4.45 °C, while between the periods 7:00 p.m.-4:00 a.m. was -5.53 °C. Furthermore, this study proves that the thermal performance of LP is climate dependent because maximum diffuser temperature recorded in the tropics was 43.18 °C which was more than twice that recorded in Beijing 23.43 °C, a monsoon influenced climate [1]. Given that February is not the hottest month in Jamaica, maximum temperature is expected to increase. Another finding from this study was that LP can provide illumination to buildings under sunny and cloudy condition. On a sunny day, LP can provide sufficient lighting to prevent the use of electric lighting on a sunny day. Research needs to be placed on quantifying its ability to reduce the overall consumption of the building.

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