Smart Light Pipe Strategies in Deep Plan Office Building in Dhaka, Bangladesh

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ABSTRACT

Asian cities, especially tropical cities of South and Southeast Asia, are in need of smart technology. One smart technology, the light pipe strategy, would alleviate the dependence on artificial lights during daylight hours. Light pipe provides possible solution by means of piping daylight into the depths of buildings. This research focuses on the potential of light pipes in Dhaka city. For the solution, horizontal light pipes have been retrofitted to the selected buildings and assessed by testing a computer model using 'Ecotect and Radiance'software. Comparative analysis was conducted between the existing and the retrofitted conditions to show the feasibility of the suggested method.

Keywords: *light pipe, deep-plan building, sustainable architecture, energy consumption*

INTRODUCTION

In the quest to enhance visual qualities and the aesthetics of spaces, daylight is considered to be the primary source of illumination available to architects. Although availability of daylight is abundant during working hours in the tropical countries like Bangladesh, artificial light still serves as the main contributor to visual environments (Ahmed and Joarder, 2007). According to O'Connor et al., (1997), dependency on daylight in office buildings has several advantages. First are an increase in productivity and a decrease in absenteeism. Second is a reduction in electric lighting and cooling loads that together represent 30% to 40% of the total energy use in a typical commercial building. Moreover energy efficient buildings are considered as good real estate investments which in turn bring better lease rates, faster investment returns and higher cash flow. Daylight also has a lower impact on the environment.

In a country like Bangladesh, this opens up a new horizon for further research as, according to Sharma (2002), Dhaka has the highest consumption of electricity in the country. It would be beneficial if daylight could be harnessed and used as an alternative means to artificial lighting. Architects are thus encouraged to consider using daylight to reduce the consumption of mechanically operated lighting system.

Middle and high-rise office buildings are associated with floor plans that have considerable depth. Recently this plan has become the preferred office layout as it provides flexibility as well as economic benefits for the modern businesses. Although this layout is preferred, mainly for daylit operations, the main disadvantage is that the daylight passively reaches only up to a 4 meter in distance from the opening on the perimeter (Garcia Hansen and Edmonds, 2003). The main reason behind dependency on electrical light is that daylight level are decreased in spaces further from the perimeter windows. Nadal (2005) points out that this process provides an uneven illumination; a high concentration near the openings and very low light levels at the deep core. This problem promotes artificial light usage, which subsequently leads to high energy consumption, thus creating the necessity of introducing an appropriate amount of daylight into the room.

To control daylight intensity and to efficiently distribute it throughout the interior space, several day lighting systems have been developed. One approach to capturing daylight and efficiently channeling it towards the core (from 6-10m) of a building is the light pipe. Previous research has shown that light transport systems (light pipes) represent a possible solution to naturally illuminate the core of deep plan buildings. This is done by piping light from the building's envelope and distributing it to the interior space (Garcia Hansen et al., 2003). Its aims are to distribute uniform illumination to the deepest part of a room in combination with side openings that eliminates the glare problems. Although the light pipe serves as a good option for illuminating the deep office cores, as daylight levels vary with location, seasons and cloud conditions, light pipes and electric lights should be integrated in order to meet lighting requirement standards (Nadal, 2005).

The main objective of this research is to examine the potential of daylight systems to illuminate the deep cores of two selected office buildings in Dhaka, Bangladesh. A computer simulation study of the performance of a horizontal light pipe system is generated for two deep office plans; each with different degrees of obstruction and two different conditions, a sunny sky and an overcast sky. The original design of the light pipe is modified according to the Dhaka's solar angle to obtain a better understanding of its performance for this particular latitude. A comparative analysis is completed based on the results to find the feasibility of light pipes in this tropical area.

The main research questions for the paper are as follows:

- Is the current situation of daylight performance satisfactory to the day lighting level standards set by the Chartered Institution of Building Services Engineers?
- Can Light Pipes be applied to address this problem?
- Are Light Pipes a feasible solution to integrate in deep plan spaces to provide adequate lighting?

Hypothesis to be tested is as follows:

The illumination levels achieved by the light pipes' simulation meets the daylight standards (300 lux for moderately easy visual tasks and 500 lux for moderately difficult general office work) set by CIBSE (The Chartered Institution of Building Services Engineers) guide 7th edition. The chart is provided in Appendix A.

REVIEW OF LITERATURE

Currently a major concern for architects to consider is energy consumption. This has been a growing concern since the last decade with the professional and theoretical communities demanding viable solutions. One possible solution that appeals to both communities is projecting natural light into interior spaces by using light transporting systems, i.e., light pipes. In 1880, William Wheeler invented a system of light pipes lined with a highly reflective coating that illuminated homes by using light from an electric arc lamp placed in the basement and directing the light via the pipes throughout the home. This technology has gone through several modifications since then and now appears to be a smart solution to provide natural illumination to areas deep within a building.

The literature, however, is scarce as not many prototypes have yet been developed. Epistemologically speaking, this research takes a positivistic approach, as it refers to the school of research that is based on apparent evidence and facts resulting from defensible scientific findings. Positivism is generally linked with quantitative research and this study directly calculates the level of illumination. Ontologically this falls within the realm of objectivism as the results obtained from this simulation are clearly objective and are independent of any social factors. It can be argued that the process was deductive in nature as the hypothesis tests the illumination levels achieved by using light pipes to meet daylight standards.

There are two types of light pipe configurations in practice today; vertical and horizontal. The vertical configuration can be found in many instances. However, its use is very limited as it can only be used in a single story bulding and in the top floor of multi storied buildings (Oakley et al., 2000, Carter, 2002, Jenkins and Muneer, 2003).Another drawback of the vertical light pipe's configuration is that it needs expensive technology as it is required to concentrate the sun's rays. Horizontal light pipe systems, on the other hand, provide a promising solution for supplying daylight to different floors of a multi storied building. One of the major advantages of this system is that the horizontal light pipes can be fitted into ceiling plenums which makes the integration into existing buildings easier and appropriate.

However, illumination from light pipes has four problems: 1) collecting light, 2) depending on solar elevation for power transmission, 3) extracting similar amounts of light along the pipe and 4) producing a uniform distribution of light within the space from a small concentrated output (Garcia Hansen and Edmonds, 2003). Solar altitude is considered the main reason effecting the performance of light pipes (Wu et al., 2008). Garcia Hansen and Edmonds, (2003) explains the current research on this matter, that of focusing on improvements to light pipe's components. They have classified various systems based on materials used to transport light. Among them is fiber optics, which are made of silicate glass or plastic. They represent very high levels of efficiency in transporting light by using total internal reflections. But the disadvantage of fiber optics is that light needs to be highly concentrated before entering the fiber, thus incurring the added costs of using complicated heliostats to concentrate daylight. Recent studies have shown that a more economical alternative to fiber optics is the use of luminescent solar concentrators that absorb natural light and emit it as fluorescent light. The fluorescent light is then transported through flexible light guides made from low cost material. Polymethyl methacrylate or PMMA follows similar principles of transporting light by internal reflections as fiber optics but comes with greater transmitting properties and relatively low costs. But current tests carried out on this system is limited to small scale buildings.

Another means of light transportation is an arrangement of lenses combined with mirrors. This system is capable of maintaining a concentrated beam of light avoiding the need of a guide. Lenses come with 92% transmittance. But the drawbacks of this system are the high costs in addition to the intricate lens mountings. Prismatic pipes are hollow structures with transparent acrylic walls and consists of precise right angles that transport the light by total internal reflection. Currently a more developed version of prismatic pipes is in use which is made out of a new thin transparent film, making the system more efficient. For the light to channel through the device this system needs complex daylight collection systems of input angles (~28°/30°). A potentially wider application in buildings is a relatively cheaper version hollow mirrored pipes. This device is coupled with different light system collections (i.e. anidolic systems, laser cut panels). Anidolic ceilings are devices that integrate compound parabolic collectors with a highly reflective guide to redirect light deeper into a room (Garcia Hansen and Edmonds, 2003).

There have been many studies of light pipes, especially in the tropics where the sun is either in the northern or the southern hemisphere depending on the time of the year. One of these studies was conducted by Chirarattananon et al., (2000) for Bangkok (lat: 13°45'N) who used Reas's method to calculated daylight luminance with a ray tracing technique and heat transfer. The study briefly explained the design of light pipes and the types of material deployed. In another study, of a high rise building in Kuala Lampur (lat: 3°7' N), the light pipes were oriented towards the west with a horizontal configuration. (García Hansen et al., 2001; García Hansen and Edmonds, 2003). The pipes used mirrored light which were coupled with laser cut light deflecting panels, also known as LCP, as sunlight collectors and diffusers. Although it is a good mean to redirect and deflect the light towards the interior, one of the drawbacks of this system is that the panels do not maintain the intensity of the light flux. As a result of the LCPs being used as collectors, the luminance value does not reach more than 200-300 lux in the afternoon. This was acceptable for ambient light, which was required by the client, but unfortunately not suitable for task light.

For Asian cities this technology appears to be a smart solution. However, this problem required some further improvements and Peron et al., (2004) conducted an annual simulation of the horizontal light pipe in Venice (lat: 45.5° N) for south facing rooms. The reflector in this study was mechanical as opposed to previous works and varied its slants to capture the sun's rays as the sun moved throughout the day. Although there were some improvements in the results from the previous models, it still had limitations that needed further investigation. In order to obtain a uniform luminance level at the work plane, the transparent glazing was reduced to 30% (from $10m^2$ at the reference case to $3m^2$), that minimized the view to the outside. Other than this small limitation, the study was complete in terms of visual comfort. The pipes obtained a uniform daylight distribution across the room with correct luminance levels and the contrast ratios.

The proposed mirrored pipes provide better results than most of the light pipes in the sense that it has the advantages of both top and side light sources. It performs like the horizontal task light that requires little glare control and can be used to illuminate every floor of a high-rise building (Kunjaranaayudhya, 2005). According to Ayers and Carter, (1995), this proposed horizontal system could be widely applied in building design. It is relatively cheaper than many other transportation systems and can also channel the light through multiple secular reflections. Efficiency of the light pipes depends on the following: the area to be illuminated, the geometric forms of the pipes, the reflectivity of the material (85%, 95%, 98% for example), the directional properties of the light source and a well collimated sunlight that can produce an efficiency of 50%. A study conducted by the Lawrence Berkeley Laboratory (LBL) evaluated the system and found out that it can redirect sunlight towards the rear of the room successfully from the façade using different reflective materials and through optimized geometry. Lawrence Berkeley Laboratory is situated at Los Angeles, CA (Latitude 34°) and the results show regular luminance level of 200 lux or more from 9 a.m. to 4 p.m. throughout the year (Beltrán et al., 1994; Beltrán et al., 1997).

The light pipes have gone through some changes from their very first model and are briefly discussed in the following section.

The first model is shown in figure 1(a). The basic light pipe plan had a rectangular section and a trapezoidal section for elevation. This is where the height is lowered towards the innermost portion of the tube. It had a central reflector of 2 feet at the front aperture for redirecting the incoming rays.

The next modification was the light pipe shown in figure 1(b) which is the light pipe shown in A but had a six feet wide aperture in front but still had the two feet wide section at the back. This configuration generated a trapezoidal section. The elevation was rectangular that was derived from the consistent height.

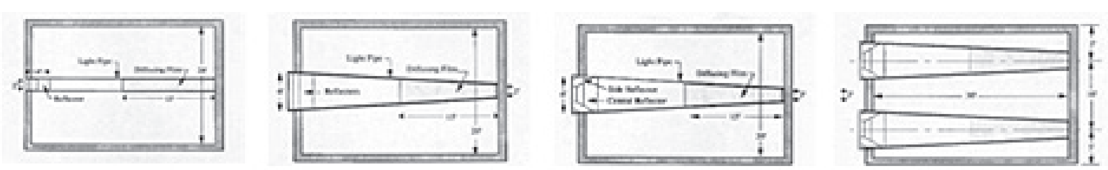
The light pipe B is shown in figure 1(c) was the next modified version. An added element was side reflectors. The side reflectors were used to reduce the number of reflections from the azimuth rays which is essential for proper transportation of light.

The latest version of the light pipe, light pipe C shown in figure 1(d), uses a double unit of the light pipe B but the width at the back is now increased to three feet instead of two feet and the elevation has now been switched to rectangular (Beltrán, Lee, and Selkowitz, 1997).

METHODOLOGY

In this research, experiments have been conducted to find the illumination level achieved by light pipes in office building with considerable depth. Computational techniques have been employed in the research to reach the final solution and statistical data analysis has been used for checking the validity of the method.

In order to illustrate the research design, two accepted methods were used. The first method uses the physical model which has a number of limitations. This process is time consuming as it may take a whole year to complete the experiments as it needs to be carried out in different weather conditions. Another issue is that the experiment must



(a) *(b)* *(c)* *(d)*

Figure 1:
(a) basic light pipe, (b) Light pipe A, (c) Light pipe B, (d) Light pipe C (Beltrán, Lee, and Selkowitz, 1997)

be carried out in the exact location and time of day. The second method, computer model simulation, appears to have diverse flexibility. With this method, experiments can be carried out anywhere in the world with proper climatic data. This method requires less time and expense compared to the previous one. It also allows changing the settings quickly and experimenting with different materials and solutions with real weather data.

The experiment starts with developing a light pipe strategy that considers the solar angles (highest and lowest) of Dhaka, Bangladesh. The considered angles are 89.6° for summer solstice at 12 p.m., 66.7° for equinox at 12 p.m. and 42.7° for winter solstice at 9 a.m. Light pipes have been assessed by testing computer models of two existing office buildings in Dhaka, each having great depth, which were retrofitted with horizontal light pipes as daylight devices. The study used the simulation software Ecotect and Radiance. Testing was carried out under both sunny and overcast sky conditions.

The two office building were selected at random. The first building is the Unique Trade Center, which is a high-rise (20 floors) office building in Dhaka, with a floor plate of 25 meters depth and 25000 sqm (approx) area. Because room dimensions, geometry and surface characteristics plays a major role in the efficiency of light pipes (Callow, 2003), the second building, People's Insurance building, was chosen for its circular floor plan in comparison to the rectangular floor plan of the Unique Trade Center. The main floor plates of People's Insurance, where office work is conducted, have a radius of 16 meters (approx). Both building designs have plans deeper than 10 meters resulting in dark cores that depend entirely on electrical lighting for illumination. Light pipes can be installed in both of these buildings in the ceiling plenums without hampering the existing layout and outlook of the exterior facade.

In terms of tools, the software Ecotect and Radiance was used because of its highly accurate ray-tracing system for analyzing and visualizing lighting design. Also there are no limitations in simulating geometry or materials.

With the help of the simulation tools, the illumination levels of the existing buildings' plans were analyzed. Then the existing plans were retrofitted with light pipes which reach up to 8 meters from the perimeter. These results were compared using simulated diagrams by Ecotect and Radiance software. The illumination level data of the two conditions were compared using graphs. Both the sunny and overcast sky conditions were considered.

DATA

The analysis of data was done quantitatively by taking measurements of luminance level. This study of light pipe performance was based on the research started by Lawrence Berkeley National Laboratory, LBNL (Beltrán et al., 1997). Therefore, the prototype characteristics used here was similar to the previous study. Design of the light pipe was modified following the local solar angle of Dhaka in figure 2(a), (b), (c).

The illumination level of the existing plans without light pipes had been checked using radiance software. Studying the results, it was clear that the light could not reach more than 4 meters from the perimeter openings. The illumination level in the deep core was around 80 – 120 lux, which was not sufficient for regular office tasks.

To counteract the problem, the existing plans were retrofitted with light pipes which would reach up to 8 meters from the perimeter of the buildings as in figure 3(a) and (b). Sun light was simulatedly captured by the light pipe through a small glazing area. It is then guided through a transport section from the collector towards the emitter optimizing the number of bounces the light makes. The collector is made of a protruded volume that has 1 foot outside the façade and also has a glazing area in the upper part. The glazing has a transmittance coefficient of T = 88%.

Taking into consideration the angle of sun in the solstices and equinoxes, the collector was made of fixed central and side reflectors. The central reflectors were meant to be used for capturing the daylight from approximately 9 a.m. to 3 p.m. whereas the side reflectors were used to capture sunbeams in oblique angles during the early morning and late afternoon hours. The central reflectors were designed to accommodate the solar altitude angles at solar noon for both equinoxes. For the current design, the latitude considered was 23.8° and the altitude for equinoxes are 66.7°, 89.6° for summer solstice and 42.7° for winter solstice. The altitude angles were found using the sun path's diagram (see chart in Appendix B) drawn with the help of 'Ecotect' software, version 2011.

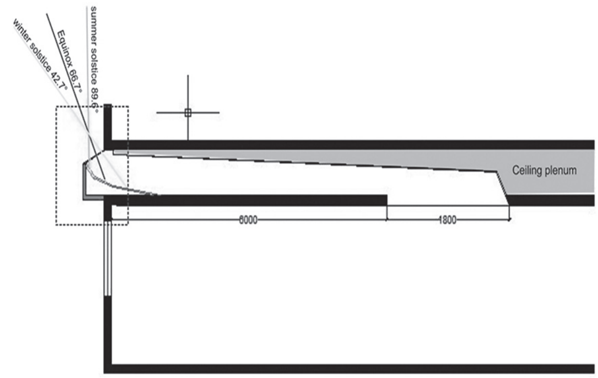


Figure 2(a):
Light pipe designed following local solar angle and installed on the ceiling plenum shown in section

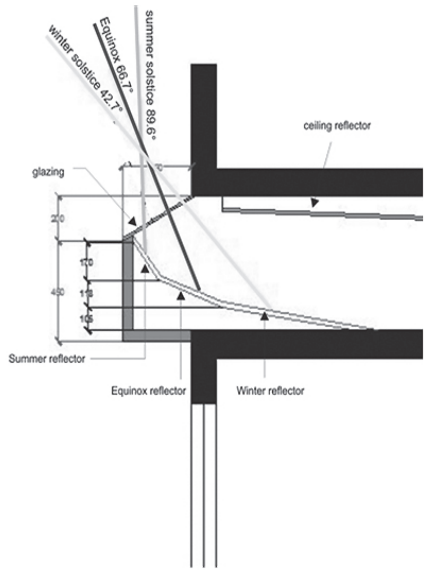


Figure 2(b):
Details of a light pipe shown in section

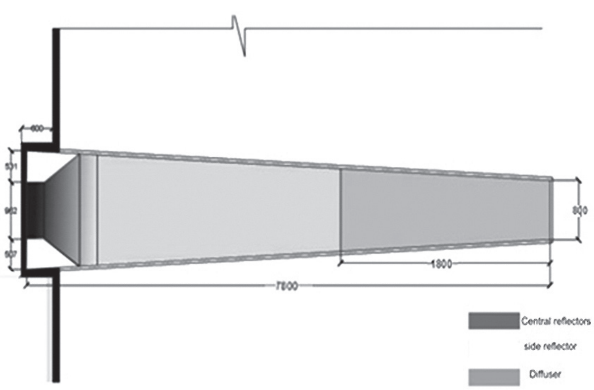
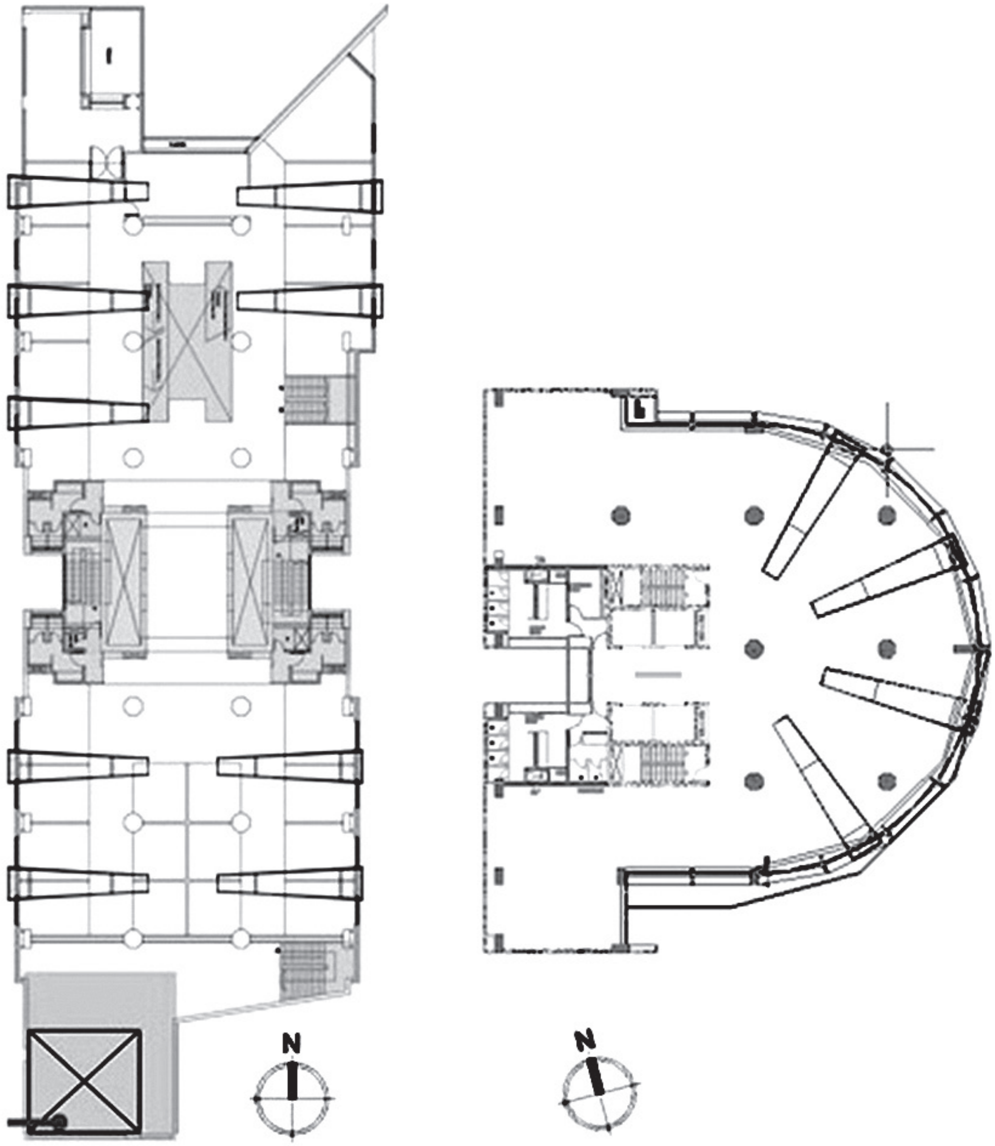


Figure 2(c):
Details of light pipes shown in the plans



(a) (b)

Figure 3:
a) case study 1 (Unique Trade Canter)
b) case study 2 (People's Insurance Building)

Case Study 1

Figure 4 indicates the distribution of daylight after retrofitting light pipes for the Unique Trade Canter. From the chart, we can see that the improvement introduced by the light pipe system at the back of the room helps obtain more uniform light levels. It combines light pipe and window contributions for both clear and overcast skies. This study was conducted on the equinox, March 21st at 9 a.m. in clear sky conditions. The improvement in the back of the space compared to the existing case can be appreciated as the space achieves luminance levels up to 300 lux which is acceptable for moderately easy visual tasks in areas such as libraries, sports and assembly halls, teaching spaces, and lecture halls (CIBSE guide, 7th edition) but not satisfactory for moderately difficult visual tasks which is 500 lux (set by CIBSE guide). Illumination levels change at different time of the day according to the movement of the sun. This shows that the light pipes attached to east façade perform throughout the greater part of working hours from 9 a.m. to 12 p.m. with the highest values at noon. The ones attached to west façade do not show satisfactory results during this period of time as shown in figure 5(a). Illumination from west side light pipes increases during the office hours (12 p.m.-3 p.m.) as shown in figure 5(b). Therefore, both light pipes in the east and west façade did not work simultaneously and serve only half of the working period. Both of them create ambient light for office work but do not reach acceptable illumination level required for task light.

An analysis of the spatial distribution of illuminance levels of the existing conditions without light pipes in clear sky, and the retrofitted condition with light pipes in clear and overcast conditions is explained later. Compared to the existing condition the simulated, retrofitted condition gives higher light levels close to the emitters due to the light pipe and clear sky. This result was in line with expectations but still the illuminance level is not enough in the middle of the space far from the light pipe emitters. Flat curves in the middle indicate that the room needs electric light for difficult office tasks since illuminance level is below 300lux. Unfortunately, illuminance levels did not change significantly with light pipes in overcast sky conditions and hence the electrical lighting system should always be kept as an option.

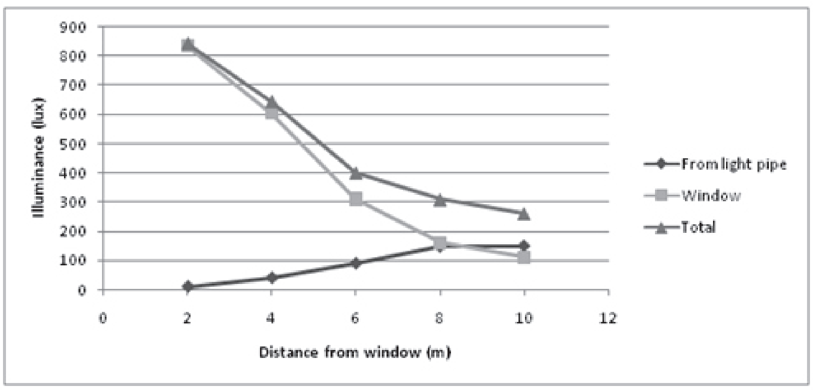


Figure 4:
Work plane illuminance (height 800 mm) longitudinally due to daylight contribution from window, light pipe and the total combination of both contributions on March 21st 9 a.m. in case study 1.

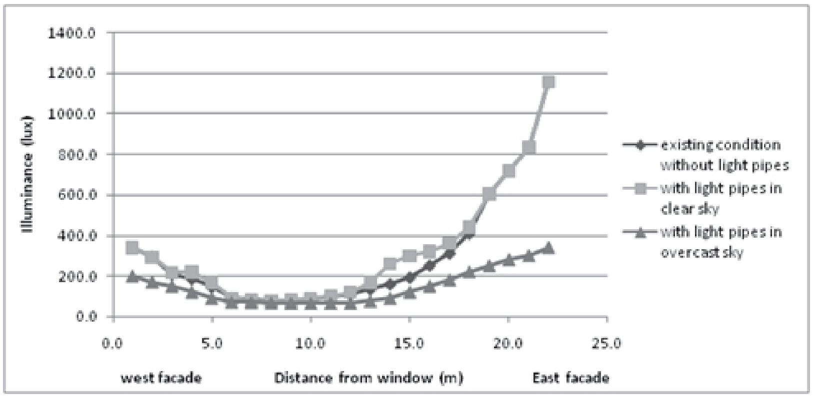


Figure 5(a):
Illuminance level comparing existing conditions and retrofitted conditions in both clear and overcast skies at 9 a.m. in case study 1

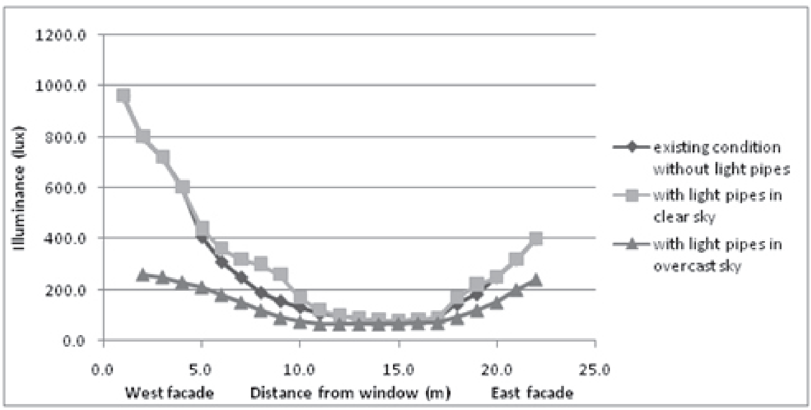


Figure 5(b):
Illuminance level comparing existing conditions and retrofitted conditions in both clear and overcast skies at 3 p.m. in case study 1

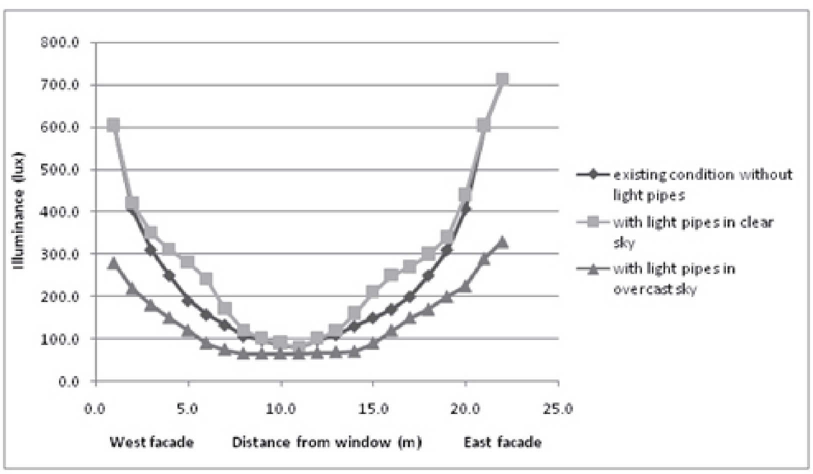


Figure 5(c):
Illuminance level comparing existing conditions and retrofitted conditions in both clear and overcast skies at 12 p.m. in case study 1

Case Study 2

Figure 6 illustrates the distribution of daylight in the second case study, the People's Insurance Building. Light pipes, with similar characteristics to case study 1, were simulated inside the ceiling plenum of the floor plan. Results showed that light pipes perform better in circular floor plan than that of rectangular configuration. In this study the light pipes were installed at the perimeter with emitters facing the central portion of the space and thus creating uniformed, concentrated light at the center. Results for this study showed that light pipes combined with windows reach up to 320 lux which is satisfactory for ambient lighting. Because light pipes were installed only on the south-east side, its serves only half of the working hours from 9 a.m. to 12 p.m. This created a need to depend on artificial lights during the afternoon. Similar to the previous case study, this study also showed that light pipes do not show substantial improvement in illumination levels during overcast conditions.

CONCLUSION

The paper is one of many that discusses the use of light pipes in office buildings of a tropical Asian city that have deep floor plans. Comparing the results received from the two case studies, it is confirmed that the light pipe system appears to be an effective resource in improving the lighing environment. It provides light levels up to 300 lux. In both cases, Light pipes are effective for approximately 6 hours which reduces the necessity of turning on the electric light during those particular periods. Although the illumination levels achieved is not sufficient for moderately difficult visual task (500 lux), light pipes contribute to the lighting required for moderately easy office work (300 lux). The study also confirms that this system is predominantly effective with sunny skies and is not suitable for overcast conditions. To study the output of side reflectors, an annual observation needs to be conducted as these are designed for equinoxes and summer solstice and to study the contribution of oblique angles.

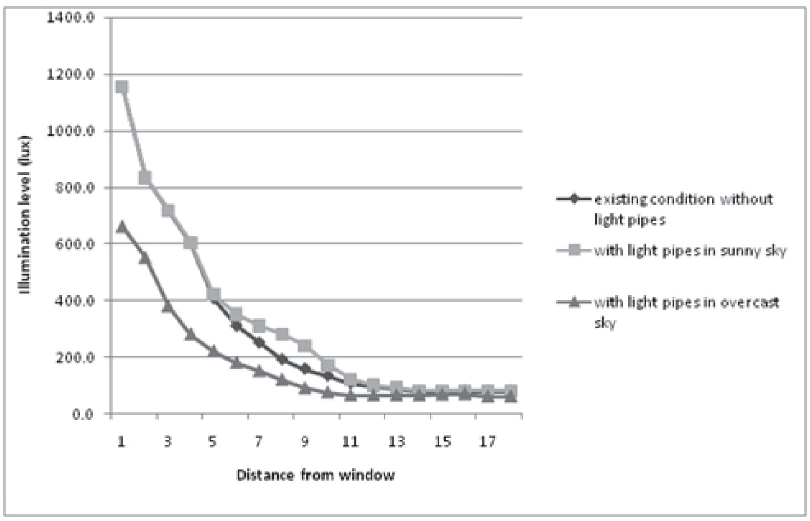


Figure 6:
Illuminance level comparing existing conditions and retrofitted conditions in both clear and overcast sky at 12 p.m. in case study 2

Further studies can be conducted concerning the assembling of the light pipe and its application in office spaces in other Asian tropical cities. This study was conducted on March 21st (equinox). Studies carried out at different times of the year, such as summer solstice and winter solstice, may bring diverse results. These results will provide good feedback on the design of the light pipes and their corresponding studies. This research was done based on the open-plan configurations of the two selected buildings, but different furniture distribution and partition heights were not considered. These factors may affect the performance of the light pipe system. More manufacturing research should be conducted using diverse materials in order to obtain better performance and the integration of the system with electrical light. The results from the paper suggest that although the light pipe is efficient in bringing daylight into office cores, there are still some limitations that need to be addressed before it can be industrialized.

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Appendix A

Standard maintained illuminance /lux	Characteristics of activity/interior	Representative activities/interiors
50	Interiors used rarely, with visual tasks confined to movement and casual seeing without perception of detail	Cable tunnels, indoor storage tanks, walkways
100	Interiors used occasionally, with visual tasks confined to movement, and casual seeing calling for only limited perception of detail	Corridors, changing rooms, bulk stores, auditoria
150	Interiors used occasionally, with visual tasks requiring some perception of detail or involving some risk to people, plant or product	Loading bays, medical stores, switchrooms plant rooms
200	Continuously occupied interiors, visual tasks not requiring perception of detail	Foyers and entrances, monitoring automatic processes, casting concrete, turbine halls, dining rooms
300	Continuously occupied interiors, visual tasks moderately easy, i.e. large details > 10 min. arc and/or high contrast	Libraries, sports and assembly halls, teaching spaces, lecture theatres, packing
500	Visual tasks moderately difficult, i.e. details to be seen are of moderate size (5–10 min. arc) and may be of low contrast; also colour judgement may be required	General offices, engine assembly, painting and spraying, kitchens, laboratories, retail shops
750	Visual tasks difficult, i.e. details to be seen are small (3–5 min. arc) and of low contrast; also good colour judgements may be required	Drawing offices, ceramic decoration, meat inspection, chain stores
1000	Visual tasks very difficult, i.e. details to be seen are very small (2–3 min. arc) and can be of very low contrast; also accurate colour judgements may be required	General inspection, electronic assembly, gauge and tool rooms, retouching paintwork, cabinet making, supermarkets
1500	Visual tasks extremely difficult, i.e. details to be seen extremely small (1–2 min. arc) and of low contrast; visual aids and local lighting may be of advantage	Fine work and inspection, hand tailoring, precision assembly
2000	Visual tasks exceptionally difficult, i.e. details to be seen exceptionally small (< 1 min. arc) with very low contrasts; visual aids and local lighting will be of advantage	Assembly of minute mechanisms, finished fabric inspection

* Maintained illuminance is defined as the average illuminance over the reference surface at the time maintenance has to be carried out by replacing lamps and/or cleaning the equipment and room surfaces

Appendix B