Improving Daylighting Performance of Mirrored Light Pipes

Passive vs. active collection systems

GARCIA HANSEN, V.[1], EDMONDS, I.[2], BELL, J. M.[3]

[1]School of Design, Queensland University of Technology, Brisbane, Australia
[2]SOLATRAN Pty Ltd, Brisbane, Australia,
[3]Faculty of Built Environment and Engineering, Queensland University of Technology, Brisbane, Australia

ABSTRACT: This paper assesses and compares the performance of two daylight collection strategies, one passive and one active, for large-scale mirrored light pipes (MLP) illuminating deep plan buildings. Both strategies use laser cut panels (LCP) as the main component of the collection system. The passive system comprises LCPs in pyramid form, whereas the active system uses a tilted LCP on a simple rotation mechanism that rotates 360° in 24 hours. Performance is assessed using scale model testing under sunny sky conditions and mathematical modelling. Results show average illuminance levels for the pyramid LCP ranging form 50 to 250 lux and 150 to 200 lux for the rotating LCPs. Both systems improve the performance of a MLP. The pyramid LCP increases the performance of a MLP by 2.5 times and the rotating LCP by 5 times, when compared to an open pipe particularly for low sun elevation angles.
Keywords: daylighting, mirrored light pipes, laser cut panels, passive daylighting collectors, active daylighting collectors

INTRODUCTION

The most critical factor in improving the performance of mirrored light pipes (MLP) is the design of the daylight collection devices. MLP are daylighting strategies capable of bringing natural light deep into the core of buildings when skylights or atria are not feasible. MLP are less complicated to build than other light transport systems (e.g. prismatic pipes, lenses), are currently cheaper than fibre optics, and potentially have wide application in building design. MLP transport light by multiple specular reflections, and as a result their performance is affected by 1) light collection, and 2) the dependence of power transmission on solar elevation. Both aspects can be improved by efficient daylight collectors.

A collection device can be passive or active. Passive implies no mobile parts, and a fixed orientation. Passive systems can collect sunlight and skylight from part of or all of the sky hemisphere. Passive collectors include anidolic concentrators, luminescent solar concentrators and light redirection collectors (e.g., heliobus). In contrast, an active system involves a mechanical sun tracking device that actively focuses direct sunlight. It has the potential to collect the maximum daylight available at any time. Some examples include heliostats, curved reflectors and Fresnel lenses.

Laser cut panels (LCPs, Fig. 1) are a simple optical material that due to its light redirecting properties, can improve daylight collection for MLP. MLP coupled to LCPs have been previously studied as passive and as simple active systems. Firstly, Edmonds et al. [1] examined a tilted LCP in a fixed position on commercially available MLP. Their study showed that LCP's improve the performance of MLP only in winter months. Secondly, Garcia Hansen & Edmonds [2] studied a pyramid LCP arrangement for larger scale MLP. This solution improved performance over fixed tilted panels and increased light output for low sun elevation angles throughout the year. However, it also revealed considerable variation in light output throughout the day. Thirdly, Travers [3] assessed rotating LCP as daylight collectors for narrow mirrored light pipes. His study suggested that rotating LCP could increase the aspect ratio of commercially available mirrored pipes up to three times. Finally, Venturi et al [4] evaluated a daylight collector where the tilt angle of the LCP was changed monthly (manually). This resulted in an improvement in winter months; however the system fails to address the variations of illuminance levels during a single day.

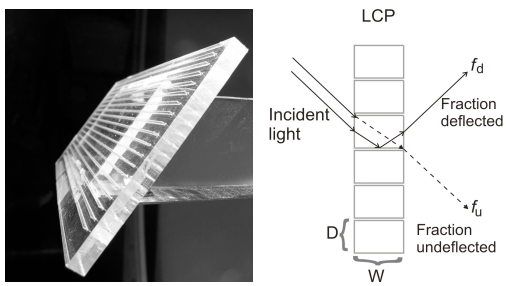

Figure 1: Laser cut panel (left) and Light deflection through a mirror light pipe (right)

This paper evaluates and compares the performance of two LCP collectors (Fig. 2), one passive and one active, coupled to large-scale vertical MLP and assesses the benefits and limitations of both solutions. The passive system comprises LCPs in a pyramid form, whereas the active system uses a tilted LCP on a simple rotating mechanism that rotates 360° in 24 hours allowing tracking of the sun's position more closely, avoiding the need for more complicated sun tracking mechanisms and sensors.

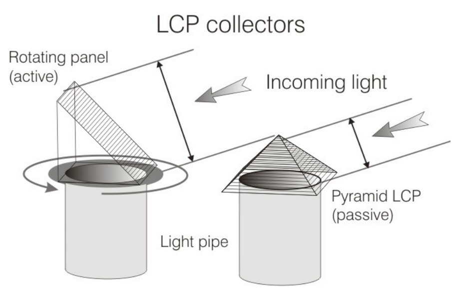

Figure 2: LCP collectors

MIRRORED LIGHT PIPES

In a MLP, light is transmitted inside the guide from the source to the output aperture by a number of multiple specular reflections at the inner wall surface of the pipe [5]. Light transmission through a MLP (Fig.3) depends on the input angle of the incident light (E), the proportions of the pipe in terms of the ratio of length (H) to cross-sectional area (W), and the reflectance of material of the guide (ϱ) [1].

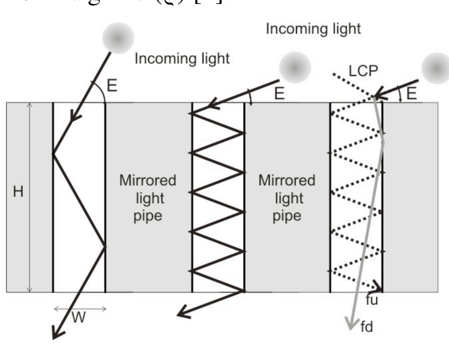

Figure 3: Light transmission through MLP pipe for high elevation angles, and low elevations with and without LCP

The effect of the angle of the incident light is apparent, for instance, when light enters the pipe at a wide angle to the pipe axis, and as a result, light will undergo numerous reflections (Fig. 3). The corresponding light loss will depend to a great extent on the reflectance of the wall material. Consequently, a more axial beam is required to minimize the number of reflections within the pipe. Thus, minimizing the number of reflections is one of the main objectives in increasing the performance of MLP, this can be achieved by enlarging the system components (but potentially at the expense of using valuable space), and/or using collection systems.

MIRRORED LIGHT PIPES COUPLED TO LCP

The theory of LCP has been explained elsewhere [6]. In general, LCPs are produced by forming a series of parallel cuts in a sheet of acrylic with a laser. The cuts produce rectangular prismatic elements. Light reaching the LCP gets deflected in the rectangular prismatic element by refraction and total internal reflection (Fig. 1). The fraction of light deflected and undeflected is a function of the incidence angle on the input face of the panel and the cut spacing (D) to the panel width ratio (W) [1]. LCP improves MLP performance by deflecting light for low elevation angles resulting in better collimation along the pipe (Fig.3).

PASSIVE SYSTEM: PYRAMID LASER CUT PANEL AS COLLECTORS

Edmonds et al. [1] showed that a tilted LCP in a fixed position fails to redirect light down the pipe for greater azimuth angles. This is because incoming light falls outside the panels' effective area of collection. This can be improved by using a pyramid LCP collector. Pyramid LCPs have been previously used as angular selective skylights, and the performance theory is described in Edmonds et al. [7]. Although a pyramid LCP has a reduced area of light collection at any one time, when compared to a tilted panel (Fig.2), it always provides panel area exposed to the incident light, thereby improving the performance of the MLP throughout the year.

ACTIVE SYSTEM: ROTATING LCP

As there is a great variation in light output throughout the day for passive LCP collector [1, 2] a rotating LCP collector that decreases the reliance of the device on sun altitude and azimuth is investigated. Rotating LCP collectors consist of a tilted LCP panel (tilt angle depends on latitude and location of the building) placed on top of a rotating mechanism. The panel revolves at a constant speed, rotating 15º every hour, completing a full 360º circle in 24 hours. The direction of rotation depends on location; the panel will rotate in anti-clockwise direction for southern latitudes and clockwise direction for northern latitudes. The system does not trace the exact position of the sun, instead, by rotating constantly at the same speed it is expected that the angle between the sun azimuth and the direction that the panel is facing is lowered, thus reducing the impact of sun azimuth in light pipe performance.

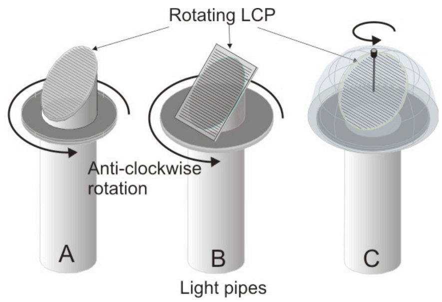

Figure 4: Rotating LCP collector

This paper focuses on this solution for vertical light pipes. Figure 4 shows schematic designs of the device. Systems A and B are panels placed on top of a rotating structure. System C, by contrast, has the panel rotated on its axis by an axle. The system could incorporate solar cells that power the engine/motor to rotate the panel.

METHODS

The method of assessment of these technologies involves the construction of working models and then testing under clear (sunny) sky conditions. The systems tested include Pyramid LCP (with different tilt angles) placed on top of the MLP, and LCP sheet tilted at different angles, and then rotated manually to simulate the 24 hour rotating LCP collector. The assessment involved: 1) the testing of the LCP collectors under real (sunny) sky conditions, 2) validation of mathematical models, and finally 3) mathematical analysis of LCP systems incorporated into a multi-storey building, to assess performance of a full-scale system in a real building situation for different times of the year.

Mathematical models In order to obtain the lumen output of the MLP for various LCP collector solutions the mathematical modelling encompasses:

1) Selection of the sky type and calculation of daylight available, in lux, at the entrance aperture of the system (I) comprised by the diffuse component (CIE uniform sky) plus the direct component of daylight calculated by Bourger's law,

2) Determination of area (A) of collection (attributed to sun elevation angle and collector geometry-see Fig.2),

3) Input luminous power (daylight available through the collecting area), I xA,

4) Light deflected and undeflected by the LCPs (LCP theory [6]),

5) Light transmission through a MLP [6],

6) Light extraction from light pipe to building at different openings (light extraction theory [8]).

Scale model testing For the experiment, a scale model of a light pipe coupled to an integrating box was built. The light pipe model comprised an acrylic tube with the following dimensions: height 1010mm, outside diameter is 103mm, and inside diameter 95mm (3 ¾"), lined with silverlux material (ϱ= 95%). Aspect ratio of the pipe is close to 11. LCP's are placed at different angles onto a 360^o protractor (with marks every 10^o). The light pipe was set up on top of an integrating box of the following dimensions: 20 cm in height, 22.5 cm in length and 19.2 cm in width. The box was painted white on the interior walls and in the ceiling has an aperture (diameter of the pipe) covered with a diffuse acrylic material. Measurements of inside the integrating box were taken for its calibration.

TESTING

Testing under clear real sky conditions of a light pipe coupled to an integrating box was undertaken on December 1st (Fig. 5), from 6:30am to 6:00pm. Location: Brisbane, Australia (latitude: 27°S, longitude: 153°E).

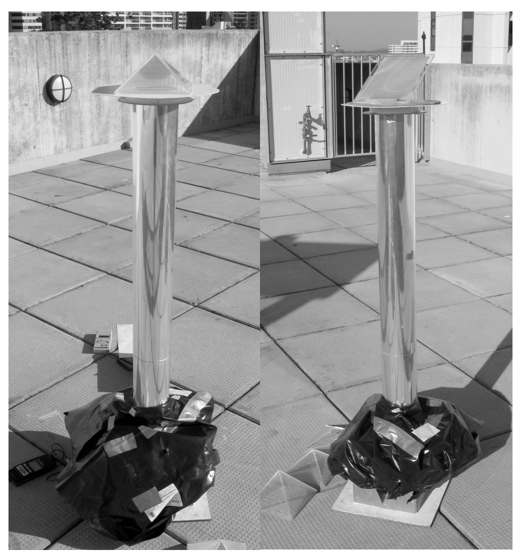

Figure 5: scale model testing under clear sky conditions

The following LCP collector systems were tested: 1) 24hour rotating panel tilted at 35^o, 2) fixed panel at 35^o facing north, 3) Pyramid LCP tilt at 35^o, 4) Pyramid

LCP tilt at 45º, 5) Pyramid LCP tilt at 55º and 6) open pipe (no collector system).

Additionally, measurements were taken of the horizontal illuminance at the beginning and at the end of each set of measurements to check that the difference in illuminance is not greater than 5%, and thus obtaining comparable results. Measurements were taken every 30 minutes. In general, the results (Fig.6) have shown that:

1) The 24 hour rotating LCP produced up to 5 times the luminous output of an open pipe, particularly for low elevation angles (lower than 40°), and early in the morning, but note that an error in the calculation of solar noon (real solar noon for Dec. 1st: 11:36am), meant that the panel was rotating 23 minutes behind. From Fig.6 it can be observed that the maximum performance for the open pipe is around 11:30am, confirming the solar noon. For the experiment, solar noon was considered at 12:00pm which explains the differences in performance for the collector in the morning and the afternoon, due to the panel running behind, increasing the deviation angle with the sun azimuth.

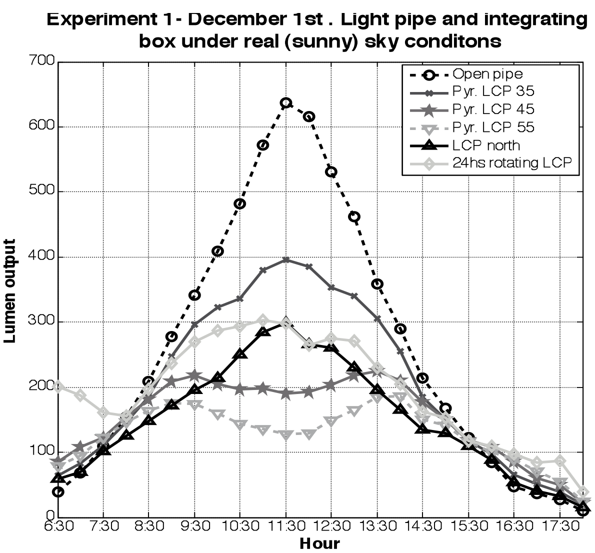

Figure 6: Testing on December 1st, for tracking and rotating LCP collectors, and pyramid LCPs at different tilts.

2) For pyramid LCP's facing north, these experiments showed that when the pyramid faces are angled at 45°, the final performance of the pipe was increased for low elevation angles by up to 2.14 times higher than an open pipe. They performed better than the 55° (2 times) and 35° (1.63 times) pyramids at lower sun elevation angles. In contrast, the pyramid LCP tilted at 35° performed better in general for higher elevation angles following the curve of the open pipe's performance. On average, the performance of all the pyramid systems is lower than the 24 hour rotating LCPs.

3) The LCP panel tilted at 35° in a fixed position (facing north) yielded the worst performance of all the collector systems. It barely increased performance at low elevation angles. The performance of this system follows very closely that of an open pipe, but did reduce luminous output at high elevation angles.

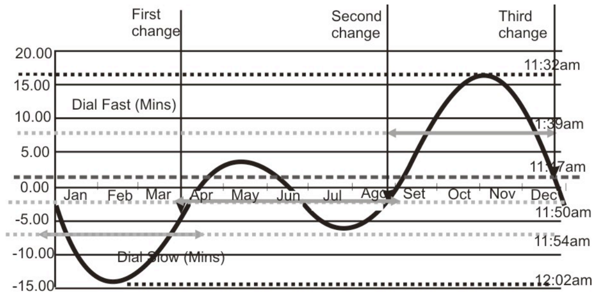

Figure 7: Equation of time

4) The sun does not pass through the meridian at the same time every day due to the elliptical form of the earth's orbit. This generates a half hour difference between the earliest and the latest time the sun reaches its highest position in the sky (solar noon) throughout the year. A half hour translated into a 7.5° deviation angle. If a 24hr rotating panel is used to reduce the deviation angle, its position (at noon) needs be adjusted at least three times a year. Fig. 7 shows variations of solar noon throughout the year. Changing the time the panel is facing north (11:39am, 11:50am and 11:54am), maintains the deviation angle with the north orientation under 2° allowing a more symmetrical performance of the system throughout the day.

Validation Fig.8 (24 hour rotating LCP) and Fig.9 (pyramid LCP) show the comparison of measured and calculated values (lumen output) under the same elevation angles. The mathematical modelling calculates the luminous power output of a light pipe with same dimensions as the one tested.

The agreement between the mathematical model and tested values is very encouraging in the case of the 24hr rotating panel. The measured and modelled values follow the same trend, with higher values obtained for the mathematical modelling results. Fig. 8 shows that having considered the solar noon at 12:00pm, which means that at noon the panel faces north, this results in a non-symmetrical performance of the light pipe during the day. When the panels reached north orientation at 11:37am (real solar noon for December 1st), the model shows a more symmetrical performance of the system.

In contrast, the pyramid LCP mathematical model (Fig.9) shows higher discrepancy. In general, they overestimate performances by 28% for low and mid range solar altitudes, and underestimate performance by around 15% for higher elevation angles. However, the model still follows a similar trend of performance as the measured values.

Generally the discrepancies in performance are a result of assumptions made during the calculations. The mathematical model for the pyramid LCP is a simplified model and does not take into account the sun azimuth angles. Nevertheless, knowing the limitation of the model and how it performs, it still provides a useful tool to further investigate the performance of these collector designs for other parameters (e.g. different elevation angles, time of the year, materials, dimensions of the pipe, etc.).

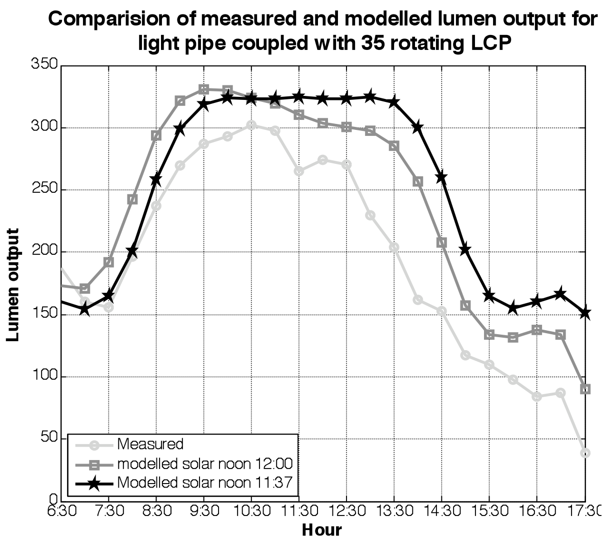

Figure 8: Comparison of measured and calculated lumens out for 24hs rotating LCP

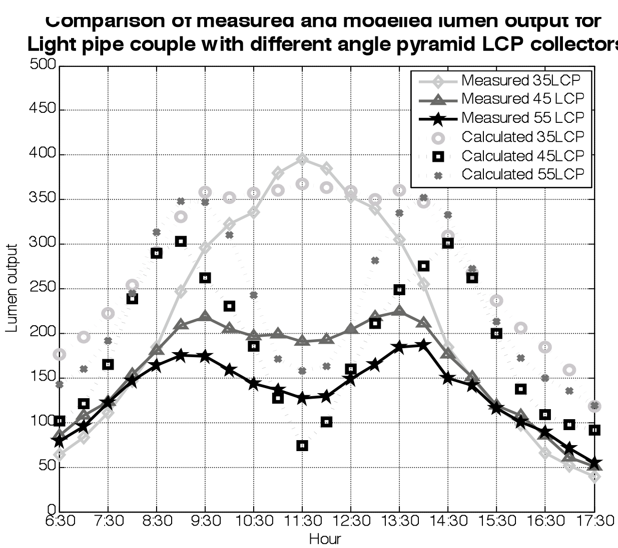

Figure 9: Comparison of measured and calculated lumens out for pyramid LCP at 35°, 45° and 55° tilt.

MATHEMATICAL MODELLING

To better understand the possibilities and limitations of a 24 hr rotating-LCP and a pyramid-LCP, mathematical analysis of the technologies was undertaken for three days (June 21st, December 21st and March 21st), representing the worst, best and intermediate situations. The analysis was done for a pipe (width: 2m, length: 19m, ϱ=95%) that illuminates 5 floors, and an area in each floor of 144m^2. The results are shown as the average illuminance from the 5 floors. Calculations for the rotating panels considers the starting time for panel rotation six hours before solar noon for each day modelled. The hours modelled, 8:00am to 5:00pm, represent working office hours. The calculations are made for Brisbane (Australia).

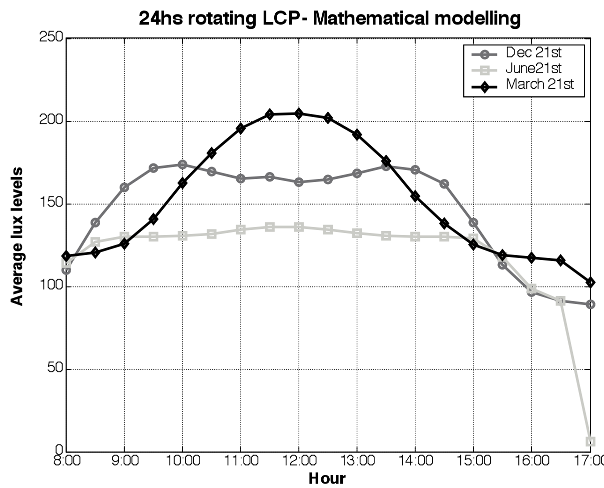

Figure 10: Modelling of 24hs rotating LCPs for December 21st, June 21st and March 21st.

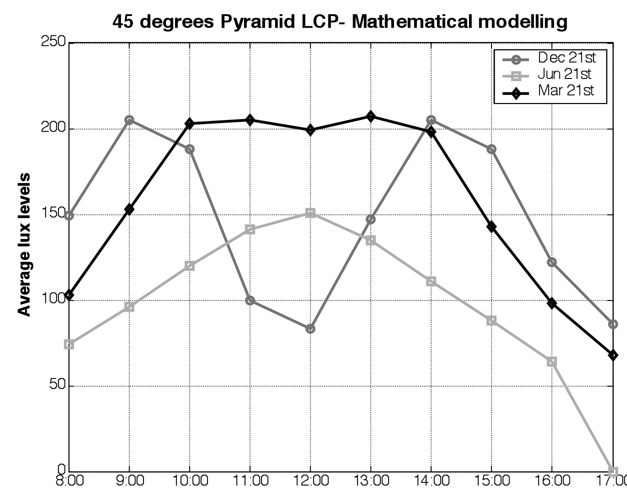

Figure 11: Modelling of pyramid LCPs at a 45° tilt for December 21st, June 21st and March 21st

Results from the 24 hr rotating LCP (Fig.10) show that on June 21^{st,} average lux values are 127lux. Lux values during the day are very similar because the system is following the sun trajectory more closely at this time of the year (like a tracking system). On March 21st average values are 157 lux, showing higher values during the middle of the day. And on December 21st the system shows a very uniform performance over the day (average values 153lux). In summary, the 24h rotating LCP improves uniformity of light pipe performance during the day, preventing low light levels due to low elevation angles, and high light levels at high sun elevation angles, especially in summer, and achieves very similar lux levels throughout the year.

Finally, the mathematical models for a pyramid LCP at a 45° tilt (Fig.11), showed an average performance of the system across the year from 75 to 200lux. Considering the testing and validation done, and aware that the performance of the system is overestimated by 28% for low elevation angles and 15% underestimated for high elevation angles, it is suggested that performance of this system could range between 50 and 250lux. It can also be observed that there is an increased variation with time (through the day and throughout the year) for this system when compared to the active collectors. However, light levels are still appropriate for ambient illumination.

CONCLUSIONS

In this study, experimental testing (scale modeling and mathematical modeling) was carried out to assess LCP daylight collectors as a passive pyramid LCP and a simple 24hour rotating LCP collector, coupled to MLP. The main aim of this study was to improve daylight collection and light transmission for MLP and to assess and compare the benefits and limitations of passive vs. active LCP collectors. The study has shown that in general, the advantages of the active system include: 1- Improvement of light levels inside the building for low sun elevations, when compared with open (5 times better) and pyramid collectors (2.5 times better); 2- More uniform distribution during the day and throughout the year, especially for winter times; and 3- improved consistency in illuminance levels (150 to 200 lux) throughout the year, suggesting that a 24hour rotating system can avoid the need for complicated sun tracking mechanisms and sensors. Some of the disadvantages of a 24hour rotating LCP collector include: 1- Starting time of the rotation panel needs to be changed at least 3 times a year to keep synchronization between the panel and sun movements, which implies more maintenance; 2- It needs mobile parts and a mechanical system, which implies more energy usage and maintenance; 3- Benefits of the system will be lost if the system does not work properly, or stops working altogether, staying in one position; 4- Having movable parts, and motors, results in a more expensive system.

Advantages of pyramid LCPs are: 1- They are a completely passive system, which implies a simpler and cheaper system that requires less maintenance, and no energy to function; and 2- The system does increase performance of the mirrored light pipe for low elevation angles, and reduces performance for high elevation angles when compared with an open system. Average illuminance levels range from 50 to 250lux. Disadvantages of pyramid LCPs include: 1- the less uniform distribution of light levels inside the building during the day and throughout the year, as results are dependant on sun elevation and azimuth; 2- the reduced area of collection, and 3- a lower performance than a rotating system.

In conclusion, 24hour rotating LCPs are successful in reducing the azimuth dependence of a mirrored light pipe coupled with LCP, achieving a more uniform and increased performance when compared with passive LCP systems. However, this improvement involves the introduction of a more complicated/expensive solution. Further studies are necessary to access the economical viability of the present technologies.

REFERENCES

1. Edmonds, I. R., Moore, G. I. & Smith, G. B. (1995) Daylighting enhancement with light pipes coupled to laser-cut light-deflecting panels. *Lighting Res. Technol.,* 27**,** 27-35.
2. Garcia Hansen, V. & Edmonds, I. R. (2003) Natural illumination of deep-plan office buildings: Light pipes strategies. *ISES Solar World Congress 2003*. Goteborg.
3. Travers, M. (1998) Daylighting via hollow mirror light guides. Queensland University of Technology. Master of Applied Science (Research)
4. Venturi, L., Wilson, M., Jacobs, A. & Solomon, J. (2006) Light piping performance enhancement using a deflecting sheet. *Lighting Res. & Tech.,* 38**,** 167-179.
5. Zastrow, Z. & Wittwer, V. (1986) Daylighting with mirror light pipes and with fluorescent planar concentrators. *SPIE 30th Annual international Technical Symposium on Optical and Optoelectronic Applied Sciences and Engineering*. San Diego, CA. USA, International Society for Optical Engine.
6. Edmonds, I. R. (1993) Performance of laser cut light deflecting panels in daylighting application. *Solar Energy Materials and Solar Cells,* 29**,** 1-26.
7. Edmonds, I. R., Jardine, P. & Rutledge, G. (1996) Daylighting with angular-selective skylights: Predicted performance. *Lighting Res. Technol.,* 28**,** 122-130.
8. Edmonds, I. R., Reppel, J. & Jardine, P. (1997) Extractors and emitters for light distribution from hollow light guides. *Lighting Res. Technol.,* 29**,** 23-32.