

Application of high-density daylight for indoor illumination

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ABSTRACT: A fiber optic solar concentrator system with a simple parabolic profile is designed and fabricated to deliver a stream of high-density solar flux into the interior of a building for indoor illumination. The system consists of a small dish concentrator (30cm in diameter), an optical fiber cable and a diffuser at the end. A series of tests are performed using a goniophotometer and spectrometer to investigate the photometric characteristics of the system in terms of luminous intensity distribution and spectral radiance, which are used in link with the actual photometric measurements for a lightless mock-up space of 4.9mx4.9mx2.6m. The illuminance on the working plane was continuously monitored at 25 points by using photometric sensors. Measurements clearly indicate the photometric characteristics of the present system where a constant level of indoor illumination is observed depending on the sky clearness.

Keywords: Fiber optic concentrator, photometric property, goniophotometer, spectrometer, indoor illumination, mock-up model

1. INTRODUCTION

In most OECD countries, lighting accounts for more than 15% of electricity consumption, and it is gradually increasing due to income growth and inefficiency in implementing quality lighting to increase occupant comfort and productivity [1-2].

Introducing natural daylight into buildings both saves energy and creates an attractive environmental condition which improves the well-being of building occupants by promoting health and physical development [3]. Active daylighting

schemes allow flexibility in applying sunlight for indoor illumination by utilizing it more aggressively. Especially, a daylighting system with movable heliostat(s) could effectively deliver sunlight to any desired location as it constantly tracks the sun. It promotes the overall affordability of utilizing natural daylight by eliminating physical constraints (in illuminating building interiors) such as the shape and orientation of a room or window, or the altitude of the sun, which passive systems may be subject to.

There are currently a number of solar lighting systems available in the market. Himawari and Solux are some well-known names where direct solar radiation is focused by using refractive fresnel lenses and guided through optical fibers (rods) to places where needed [4]. The optical lenses applied with sufficiently low aberration, however, may be excessive in weight and cost undermining their cost-effectiveness.

Unlike those with optical lenses, some systems hire mirrored dish concentrators to capture and focus sunlight into fiber optic strands. This mechanism has been explored by a number of companies and research laboratories to develop more advanced schemes in piping sunlight into buildings [5, 6]. The purpose of this study is to evaluate the feasibility of using small parabolic mini-dish concentrators (diameter < 30cm) for a daylighting system, which is rather easy to install, operate and maintain. Using small concentrators also gives an advantage in its appearance as the installation does not push out to catch one's eye.

Unlike the conventional system employing large dish concentrators (diameter > 1m) prone to high wind drag, mini-dish concentrators offer many obvious advantages as they do not require strong foundation or structure for installation and thus, preclude exorbitant start-up costs. Even when subject to high wind velocities on occasions of strong winds from the ambient in certain times of the year, the mini-dish concentrators experience relatively low wind drag requiring rather inexpensive and light structures to hold them when they are placed on roofs of buildings [8, 9].

Above all, the mini-dish concentrators could comprise a distributed daylighting system where the movement of each individual concentrator is directed by a remote-master sun tracker disseminating the information (on coordinates) onto the distributed receivers which operate the stepper motors of each mini-dish. This distributed concept implies that should one

dish mal-function, the rest of the mini-dishes can still be operational.

If needed, a standalone system could be considered in its operation utilizing the power generated by PV modules as each dish is small and light-weighted, utilizing compact digital controls and small gearing motors for the tracking of the sun. A small fraction of the power from the PV modules may be enough to operate these mini-motors (digitally controlled) for tracking purposes.

2. Design and fabrication of fiber optic solar concentrator

2.1 Design concept

Fig. 1 (a) shows the design concept of the original fiber concentrator unit, which consists of three major components: a parabolic dish concentrator, a flat mirror (2nd reflecting mirror), and a homogenizer.

As sun rays impinge on the parabolic dish (30cm in diameter), they are focused onto a small centrally-located mirror (2nd reflector mirror) which is placed on the bottom side of the transparent glass cover to avoid dust deposition on the reflector and facilitate cleaning. The 2nd reflecting mirror directs the focused sunlight into the receiving aperture of a homogenizer (a highly reflective piece of tubing : multi-sided or circular tube with secular mirror surfaces) whose role is to provide a passage for light before it enters the optical fiber bundles connected to a luminaire for terminal lighting.

To elicit the most effective way to collect and transmit sunlight to the designated position, three different schemes were tested for the 2nd reflecting mirror and homogenizer. First, a flat mirror and a tapered stainless steel pipe were used as it deemed rather straightforward. Second, a concave mirror with a short piece of highly reflective aluminium tubing was employed. Lastly, a convex mirror was used in place of the concave mirror in the second configuration.

Using a small plane mirror (diameter: 15mm) requires a taller homogenizer as its focal point should fall within the receiving aperture of a homogenizer. This restriction could be somewhat eased by using a larger plane mirror as long as it does not block the incoming sun rays near the center. A concave or convex mirror allow the use of a fairly short homogenizer as they could downstream solar rays without any divergence securing a sufficient amount of beam radiation. However, the concave mirror calls for a larger (in diameter) homogenizer and very precise positioning of the mirror. Utmost care should be exercised in this regard.

To test if all of the components designed for the system function as desired, a forward raytracing software package, Photopia, was employed at the last stage of the design analysis, [10].

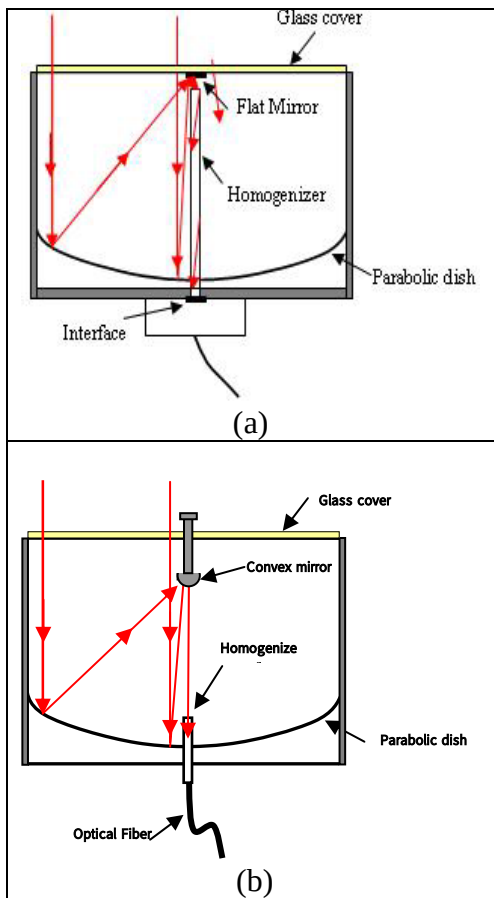


Figure 1: The design concept of the mini-dish daylighting system using different

second mirrors(reflectors): (a) flat mirror, (b) convex(concave) mirror.

Fig. 2 shows an example of the fiber optic mini-dish solar concentrator daylighting system installed on the roof of a building employing the distributed concept as aforementioned in the previous section. As shown, it comprises with a number of concentrator modules (units) where the master module equipped with a solar tracker controls the movement of slave modules. The control logic involved in the operation of the system is given in Fig. 3. An internal clock mechanism, sun sensors and a microprocessor could make a simple solar tracker to determine the exact solar position aligning the concentrators directly against the sun.

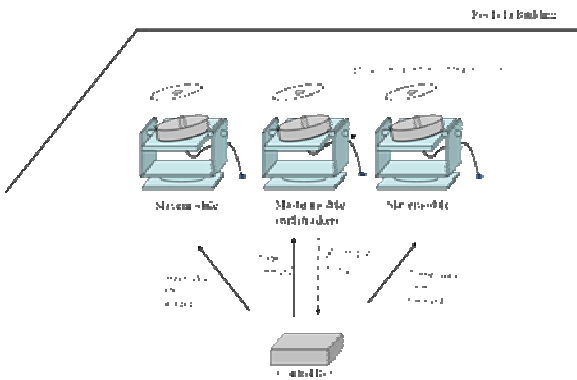


Figure 2: A fiber optic mini-dish solar concentrator daylighting system installed on the roof of a building

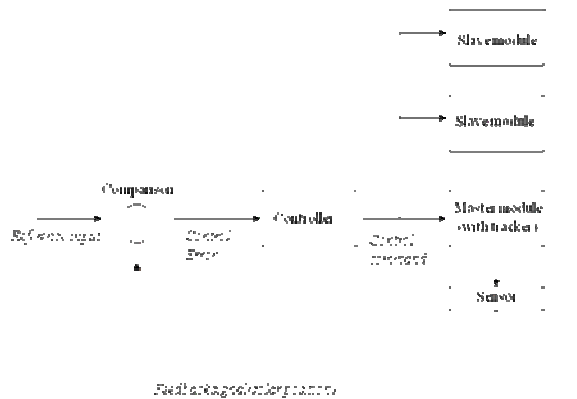


Figure 3: Control logic of the daylighting system

2.2 Fabrication

The mini-dish aforementioned is prepared by cutting an aluminum block on a CNC milling machine. Its diameter is 30cm and has a vertical focal distance of 16.25cm from the vertex at the bottom. A 2cm hole is drilled at the vertex to facilitate the joining of the homogenizer and optical fiber bundles of 5m in length [11]. When a flat mirror is used for the 2nd reflection mirror, the homogenizer made with a tapered stainless steel pipe is employed whose upper and lower IDs are 3mm and 10mm, respectively. A smooth and reflective inner surface is essential to reduce the losses in transmitting sun rays as they travel downward inside the homogenizer. The homogenizer is supported by its own stainless-steel conduit which allows the necessary positioning rigidity and accuracy for the dish assembly.

To support the glass cover on top, where a round mirror 15mm in diameter is adhered at the center of its bottom surface, an acrylic pipe of 26cm in diameter is used. Its height is 186mm and the mini-dish is fitted in from its lower end. This allows a close look from the side to observe its operation in concentrating incoming solar rays onto the small opening of the homogenizer via mirror. Fig. 4 gives a photo of the system with one concentrator unit.



Figure 4: A fiber optic solar daylighting system with one concentrator unit.

3. Photometric analysis of luminaire

A series of tests were carried out to investigate the photometric properties of the diffuser at the end of the optical fiber cable for indoor illumination. The measured data provide crucial information in designing the most optimum conditions for the system.

3.1 Goniophotometer measurements

A goniophotometer measures the spatial distribution of a radiation source and displays the photometric properties of light. It provides viable information for a radiant source such as light distribution profiles, luminous intensity, luminance and other major photometric data which are essential in designing a luminaire for indoor illumination [12, 13]. Fig. 5 shows the measurement by a goniophotometer (Model:DP-1600) to obtain the luminous intensity distribution of diffusers (optical lenses: semi-convex and concave) used at the end of the optical cable for indoor illumination.

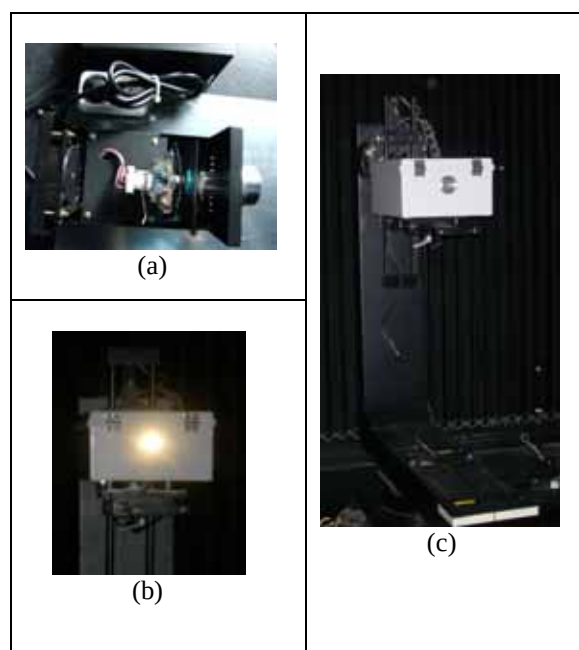


Figure 5: Goniophotometer measurements for luminous intensity distribution: (a) a test kit with a 50W halogen lamp, (b) light

emanating from diffuser, (c) test kit mounted on goniophotometer

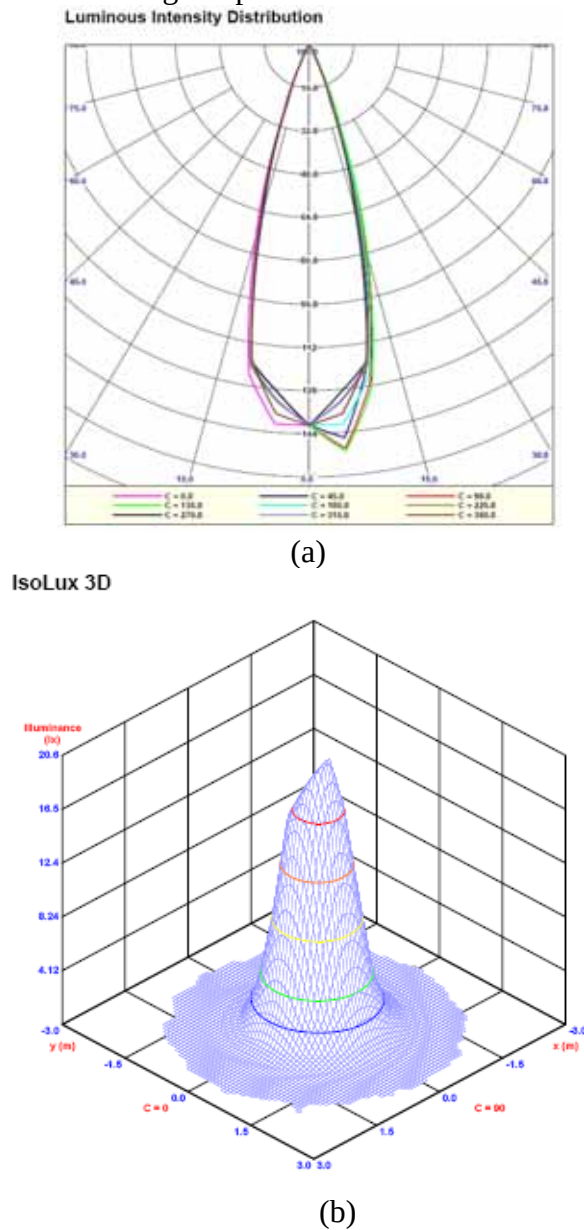


Figure 6: Luminous intensity distribution of the semi-convex lens : (a) 2D, (b) 3D presentation

Figs 6 and 7 are the luminous intensity distribution for the semi-convex and concave lens, respectively.

As shown in these figures, the concave lens spread light somewhat more than the semi-convex lens as expected. The focal point of the semi-convex lens appears to be fairly short as light immediately emanates

from it without any appreciable converging patterns.

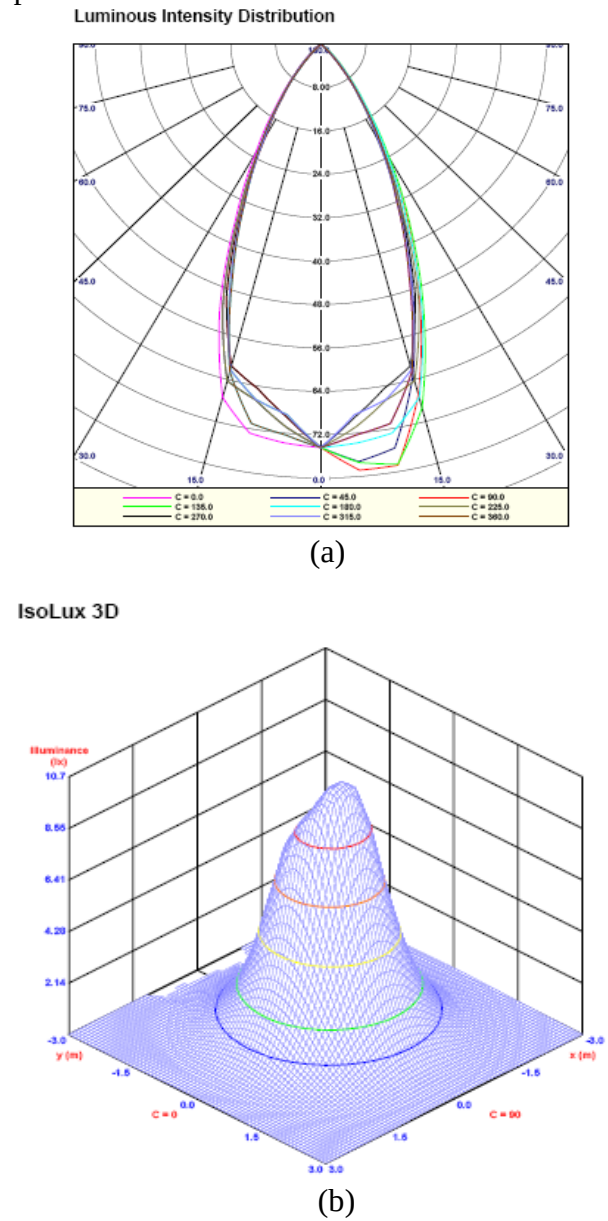


Figure 7: Luminous intensity distribution of the concave lens : (a) 2D, (b) 3D presentation

Some asymmetry observed in 2D presentations could have been caused by wobbling motions of the test kit during measurements.

3.2 Spectroradiometric measurements

A spectrometer is an optical instrument used to measure optical properties of light sources over a specific portion of the

electromagnetic spectrum [14]. In Figs 8-10, the spectral distribution of light measured by a spectrometer (Spectroscan 650) is given as it emanates from diffusers. These plots are produced using the prototype mini-dish daylighting system when exposed to actual sky conditions.

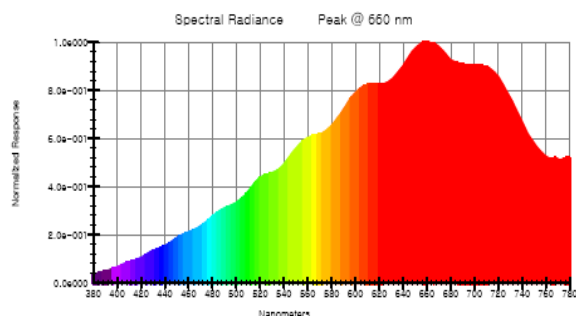


Figure 8: Spectral radiance when the semi-convex lens is used

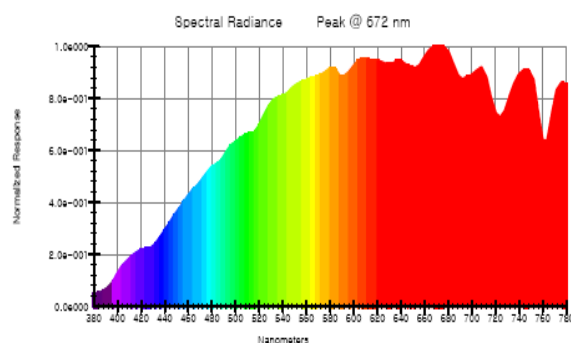


Figure 9: Spectral radiance when the concave lens is used

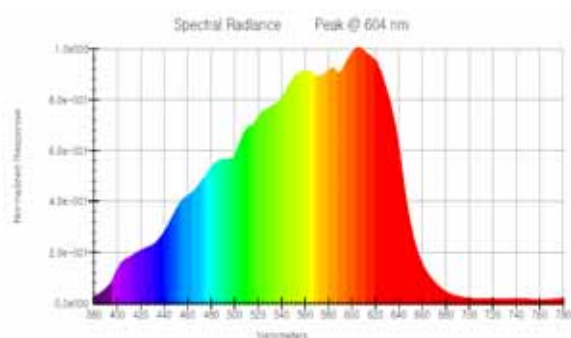


Figure 10: Spectral radiance when the concave lens is used with an IR filter (at the homogenizer inlet)

Fig. 8 and 9 show the spectral radiance distribution of light emerging from the convex and concave lenses at the end of the

optical cable, where striking differences are observable throughout the wavelength. This demonstrates the alteration of light properties as it undergoes different optical paths in a medium. That is, light entering a lens can be altered in many different ways according, to the composition, size, thickness and curvature. Fig. 10 clearly shows the effect of an IR filter placed at the inlet of the homogenizer tube. The IR portion of light ($>600\text{nm}$) is almost blocked.

4. Daylighting performance assessment

4.1 Description of the test module

Measurements were carried out on a simple architectural object – a single windowless space – in order to obtain the photometric data of light introduced by the mini-dish daylighting system under different sky conditions, Fig. 11.

The module was situated on the roof of a 5-storey engineering building at Kyung Hee University (the Light and Architectural Environmental National Laboratory: LAEL) in Korea (Latitude: 37. 2 N, Longitude: 127 E). It has a floor area of 24m^2 , which is 4.9m deep, 4.9m wide and 2.6m high. The internal surfaces are lightly coloured (walls: ivory painted sandwich panel, floor: beige asphalt tile, ceiling: white textured tile). The respective reflectance of the ceiling, wall, and floor were measured to be 0.87, 0.68 and 0.51.

4.2 Measurements

Fig. 11 shows the experimental layout hired in the present analysis. A diffuser is placed at the centre of the ceiling making a mono-point ceiling luminaire, which pipes light from the solar concentrator to the interior via 5m optical cable. Three different options are tested for the diffuser as it disperses light in different ways producing discrepancies in indoor illumination. Of these, the two options (using 33mm convex and concave lenses) are already tested for their photometric properties, i. e., spatial

light distribution profiles and spectral distribution in the previous section.

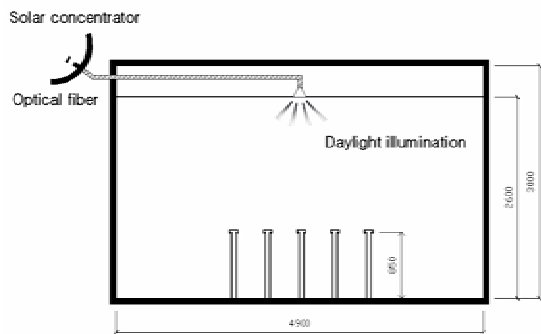


Figure 11: Experimental layout to measure the photometric properties of the daylighting system.

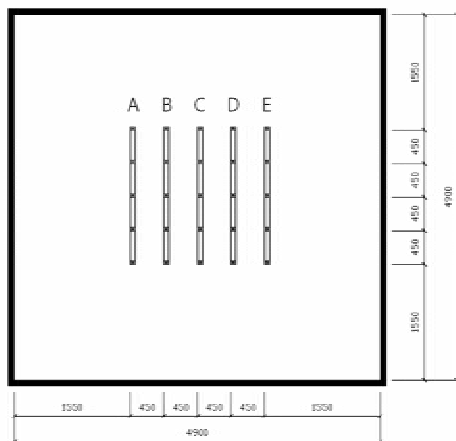


Figure 12: Location of the photometric sensors in the test module



Figure 13: Light illuminating in the test module

The indoor illuminance was measured using 25 photosensors (Li-cor photometers) deployed horizontally and vertically at a

regular interval of 45cm by specially preparing 5 rows of portable stands to provide height adjustment of 85cm recommended for the workplane (Korean Standard). Also measured were the exterior illuminance and global horizontal radiation (Eppley Pyronmeter).

The output data from the sensors were scanned every three seconds and stored using a computer based data processing system (Agilent 4.1).

4. Results and Discussion

Performance assessment for daylighting is generally more complicated than for electric lighting. Determination of the illuminance on a surface requires the inclusion of the time-varying characteristics of the sky and sun besides the changing spatial relationship between the sun and its illuminating surface.

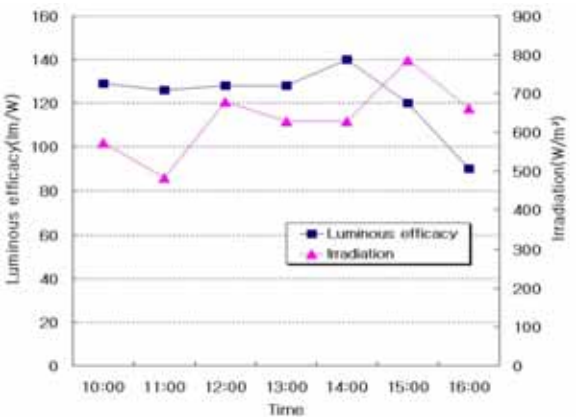
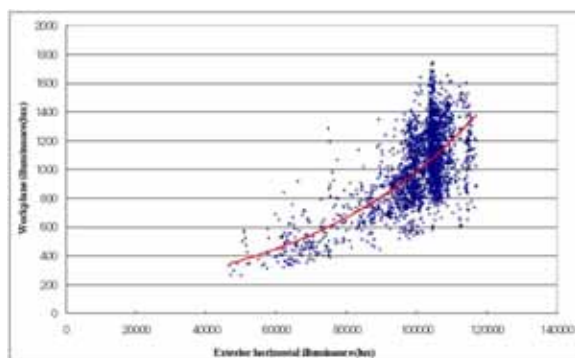


Figure 14: Luminous efficacy at different times during the measurement.

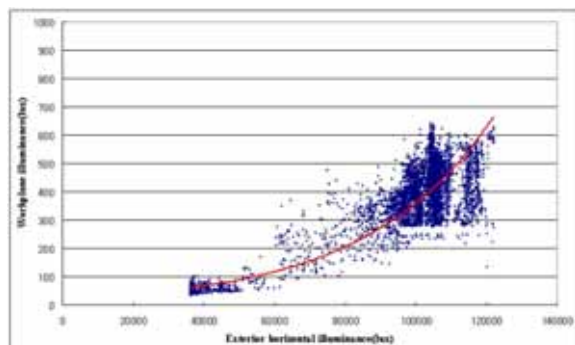
Fig. 14 shows the hourly averaged values of the luminous efficacy calculated from the measured fluxes of luminous power and solar irradiation. By comparing luminous efficacies and solar irradiation, the change in sky conditions could be readily realized during the measurement. During the initial four hours, the luminous efficacy remains almost constant indicating little change in sky conditions. In the afternoon hours,

however, it declines as the sunlight becomes more intense.

Depending on its location, the photometric sensor reads quite a different number in its magnitude. The one just below the luminaire reads the highest complying with the cosine law of illumination. At the exterior global illuminance of 104,470 lux, it measured 1,744 lux whereas 632 lux was displayed at the neighboring sensors 45cm away from it. It is worthwhile to note that the indoor illuminance does not necessarily correspond to the outdoor illuminance. As shown, there are many measurements that exceed 104,470 lux. This is due to the dominance of the diffuse over the beam component in solar irradiation.



(a)



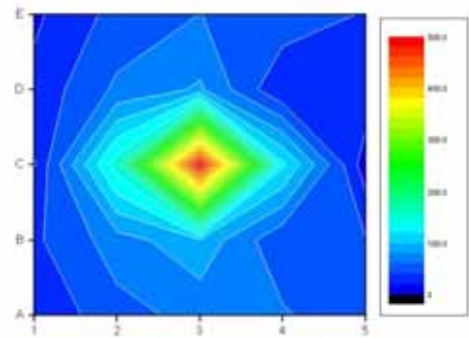
(b)

Figure 15: Workplane illuminance vs. exterior illuminance; (a) at the center of midline (c in Fig. 12), (b) 45cm from the center of midline

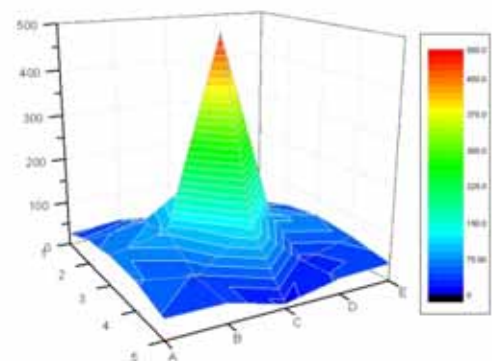
There exists a correlation between the workplane and exterior global illuminance, as shown in Fig. 15. The majority of

measured data clusters along the trend line given in terms of an exponential function:

$$(a) y = 22.087e^{3 \times 10^{-5} x}, (b) y = 138.12e^{2 \times 10^{-5} x}.$$

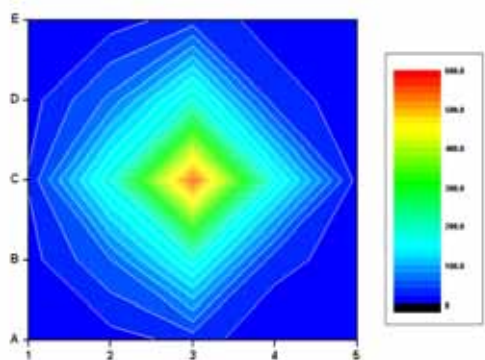


(a)



(b)

Figure 16: Iso-illuminance contour plots when no optical device (lens) is used at the end of the fiber cable to diffuse light: (a) 2D, (b) 3D



(a)

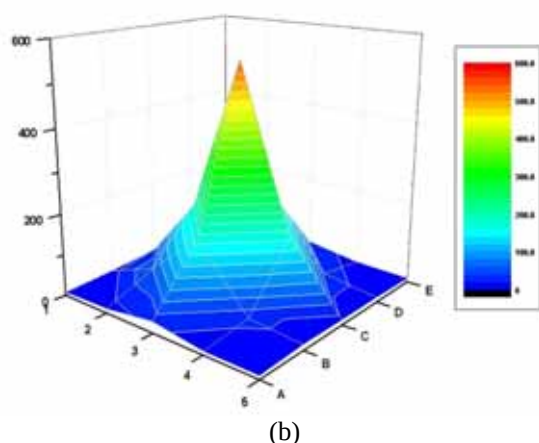


Figure 17: Iso-illuminance contour plots when a concave lens is used at the end of the fiber cable to diffuse light: (a) 2D, (b) 3D

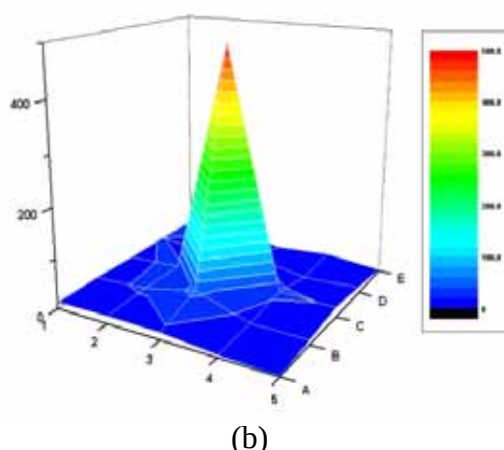
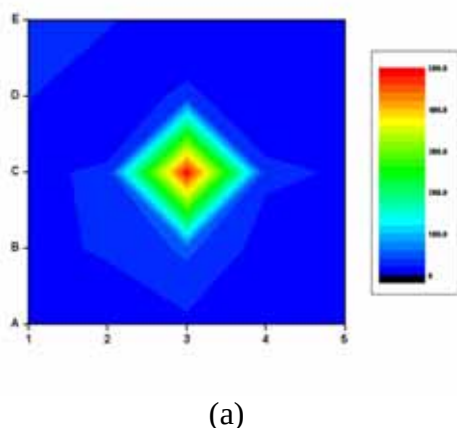


Figure 18: Iso-illuminance contour plots when a semi-convex lens is used at the end of the fiber cable to diffuse light: (a) 2D, (b) 3D

Figs. 16, 17 and 18 are 2D and 3D plots of mean illuminance distribution for the

three different cases considered in this work to diffuse light as it pipes through the optical fiber cable. Fig. 16 represents the case when no diffuser is applied. A rhombic shape of symmetry is observed in the 2D contour plot locating the highest illuminance level at the centre directly below the luminaire. Similar results are obtained for the other cases although there exist some differences in the areal coverage of iso-illuminance contours.

Of the three cases compared, the concave lens has shown the widest light distribution angle whereas the semi-convex lens seems to have the smallest light spreading ability. This agrees well with the results of the photometric analysis using a gonio-photometer introduced in section 3.

5. CONCLUSIONS

An energy-saving and sustainable design strategy could be effectively applied in exploiting daylight, which not only decreases CO₂ emissions but promotes occupant satisfaction by creating the most ideal condition possible for a space. The mini-dish solar daylighting system introduced provides an exciting new means of implementing these benefits by hiring a simple mechanism to collect and distribute natural light into a space.

Those results obtained by a series of tests using photometric instruments have established an informative and comprehensive assessment of the system. In order to determine the work plane illuminance generated by the system, the spatial distribution of light emerging from the optical cable needs to be verified. Of the 3 cases tested, the concave lens spreads the light out most widely whereas the semi-convex lens has shown the smallest light spreading ability. As for the indoor illuminance, a maximum reading of 1,744 lux was reached at the exterior global illuminance of 104,470 lux which corresponds to the light factor of 1.7%. It is also worthwhile to note that the indoor

illuminance is not necessarily proportionate to the outdoor illuminance. This is because our system tracks the sun utilizing only the beam component of solar irradiation.

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REFERENCES

- [1] KIER, A Report on the Analysis and Planning of Energy & Resource Technologies, 2005.
- [2] Olgyay, V. W. Architectural Lighting, McGraw-Hill, New York, 2002.
- [3] Augustesen, C., Brandt U., Dietrich, U., Friederici, A., Geissmar-Brandt, C., Kristensen, P. T., Madsen, M., Storch, A., Wand, B., Lighting Design, Birkhäuser, 2006.
- [4] <http://www.himawari-net.co.jp/>
- [5] Rea, M. S., The IESNA Lighting Handbook Ninth Edition, IESNA Publications Department, 2000.
- [6] POHL, W. and ANSELM, C., "Review of Existing Heliostats", European Commission DG XII (2000).
- [7] <http://www.sunlight-direct.com/>
- [8] Han, H. and Kim, J. T., Design and Preliminary Performance Test of a Daylighting Device with Mini-dishes, Proceedings of SET2006, Vicenza, Italy, 2006.
- [9] Feuermann, D. and Gordon, J. M., High-concentration Photovoltaic Designs Based on Miniature Parabolic Dishes, Solar Energy, Vol. 70, No. 5, pp. 423-430, 2001.
- [10] Han, H., Dutton, S., Riffat, S., Kim, J. T., Performance Prediction of Fiber Optic Concentrators for Natural Lighting, Proceedings of SET2007, Santiago, Chile, 2007.
- [11] Hecht, J., Understanding Fiber Optics, Pearson Education, Inc., Upper Saddle River, New Jersey 07458, 2006.
- [12] Andersen, M., Validation of the performance of a new bidirectional video-goniophotometer, Lighting Res. Technol. Vol. 38, No. 4, 2006.
- [13] Muñoz-Martínez, V. F., Serón-Barba, J., Molina-Mesa, R., Gómez-de-Gabriel, J. M., Fernández-Lozano, J., García-Cerezo, A., Double reflection goniophotometer, Metrologia, Vol. 43, No. 3, pp. 185-194, 2006.
- [14] Schlegel, G. O., Burkholder, F. W., Klein, S. A., Beckman, W. A., Wood, B. D., Muhs, J. D., Analysis of a full spectrum hybrid lighting system, Vol. 76, No. 4, 359-368, 2003.
- [15] Tsangrassoulis, A., Doulos, L., Santamouris, M., Fontoynt, M., Maamari, F., Wilson, M., Jacobs, A., Solomon, J., Zimmerman, A., Pohl, W., Mihalakakou, G., On the energy efficiency of a prototype hybrid daylighting system, Solar Energy, Vol. 79, No. 1, pp. 56-64, 2005.
- [16] Rosemann, A., Kaase, H., Lightpipe applications for daylighting systems, Solar Energy, Vol. 78, No. 6, 772-780, 2004.
- [17] A Report of IEA SHC Task 21, Daylight in Buildings, 2000.
- [18] Duffie, A. D. and Beckmann, W. A., Solar Engineering of Thermal Processes, John Wiley & Sons, 1980.
- [19] Szokolay, S. V., Introduction to Architectural Science – The Basis of Sustainable Design, Architectural Press, 2005.
- [20] Nabil A. and Mardaljevic, J., Useful daylight illuminances: A replacement for daylight factors, Energy and Buildings, Vol. 38, pp. 905-913, 2006.