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Design, Fabrication and Performance Analysis of Fibre Optic Concentrators for Daylighting

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자연채광을 위한 화이버 광학 집광기의 설계, 제작 및 성능 평가

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Abstract

자연광의 이용은 큰 어려움 없이 지속 가능한 에너지 기술을 구현할 수 있는 방안으로 고려되고 있다. 여러 개의 작은 반사경을 적용한 태양 추적식 자연채광 시스템은 비교적 단순한 메카니즘을 적용하여 그 성능과 효율성의 극대화를 꾀할 수 있으며, 또한 그 제작, 설치 작동 그리고 활용성에서 상당한 이점이 있다. 본 연구에서는 작은 mini-dish형 반사경(직경<30cm 이하)을 이용한 화이버 광학 집광기의 설계, 제작 및 작동 특성에 대하여 소개하고, 아울러 광추적 프로그램인 Photopia를 이용하여 그 성능에 대한 시뮬레이션을 수행하였다. 주요 구성 요소에서의 광추적에 의한 시뮬레이션 결과치는 실제 시스템의 설계 및 성능 예측에 중요한 기술적 데이터를 제공하며, 특히 실측이 곤란한 측정 면에서의 빛의 경로 해석에 유용하게 적용될 수 있다.

Keywords : 자연채광(Daylighting), 소형 반사경(Mini-dish), 시뮬레이션(Simulation), 포토피아(Photopia)

1. Introduction

The control of emissions of green house gases in every sector of society had an effect on building energy solutions accelerating the development and introduction of sustainable

and eco-friendly technologies in architecture. This rather became a global trend and there are reports on energy savings of 20 ~ 30% by utilizing natural daylight in buildings¹⁾.

Daylight has many problems in its utilization as it is intermittent, uncontrollable in brightness and carries heat as well as

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glare. It is, however, considered in the first place when implementing a healthy and comfortable indoor environment²⁾. According to various reports, daylight improves the productivity of workers and favored by most (90%) of the hospitalized patients. It even has shown some effect in shortening the duration of hospitalized treatment for many patients.

There are a number of important considerations to be made for existing systems to introduce natural light for those spaces without any opening to the outdoors or located too far from any openings. Of these, initial cost, maintenance expenses and robustness in system operation are the major ones to be accounted for. Often, there have been cases with excessive costs or expenses. Many building owners hesitate to apply new systems even though they offer many features that no artificial lighting system can afford³⁾.

The fibre optic concentrator system studied in this work is rather simple to fabricate and install when compared to those already in the market. Unlike skylights and windows, the system allows the user to have a control over where and how sunlight is to be used within a building and employs supplemental electric lighting if required to automatically maintain a constant level of illumination⁴⁾.

This paper briefly introduces various aspects of the fibre optic concentrator system using small parabolic reflectors and analyzes its functional performance by employing a ray tracing software package.

2. DESIGN AND FABRICATION

2.1 Design Concept

A recent survey of solar daylighting systems has emerged with a consensus among the research community that the cost effective way for solar applications in the real world should be identified with the effective use of mass production techniques for its components, starting from the receiver, means for transmitting light and the device for terminal lighting. The established mass production techniques would yield inexpensive components and thus, rendering real solar - economic competitions between active daylight systems and the conventional passive schemes integrated with architecture.

Instead of the conventionally large or big dish (adopted till today) with diameter of the order of tens of meters, small mini-dishes offer many obvious advantages:

- (i) Wind drag when subjected to high wind velocities on occasions of strong winds from the ambient in certain times of the year and hence, inexpensive and light structures are used to hold these mini-dishes when they are placed on roof of buildings.
- (ii) Distributed concept of mini-dishes rather than the big dish concept used, hitherto, enables designers to tap on the well-established but low-cost mass production processes for the manufacture of these dishes. For example, the mini-dishes could be stamped or molded and silver-reflectors are glued onto the

surfaces. Cost reduction from such mass production would be enormous when compared with the big dish fabrication.

The vision of incorporating mass production technology at every level of component design is thus what we are advocating here in this paper. We believe that only through the mass production of components of any solar system could lower the unit cost and overcoming cost-entry barrier present in today's market. Thus, the motivation for the proposed mini-dish system is that every component used in the design would be amiable towards mass manufacturing process. Our main objective is that this system should compete to its fullest potential in the real world markets.

2.2 Design of a Mini-Dish

Each mini-dish is designed with a simple parabolic profile, concentrating sun light (after the glass glazing cover to avoid dust deposition on the reflector and facilitate cleaning) onto a centrally-located small mirror which is placed on the bottom side of the transparent cover. The focused sun light is reflected by the mirror surfaces onto a focal point where the receiving aperture of a homogenizer (multi-sided or circular tube with specular mirror surfaces) is located.

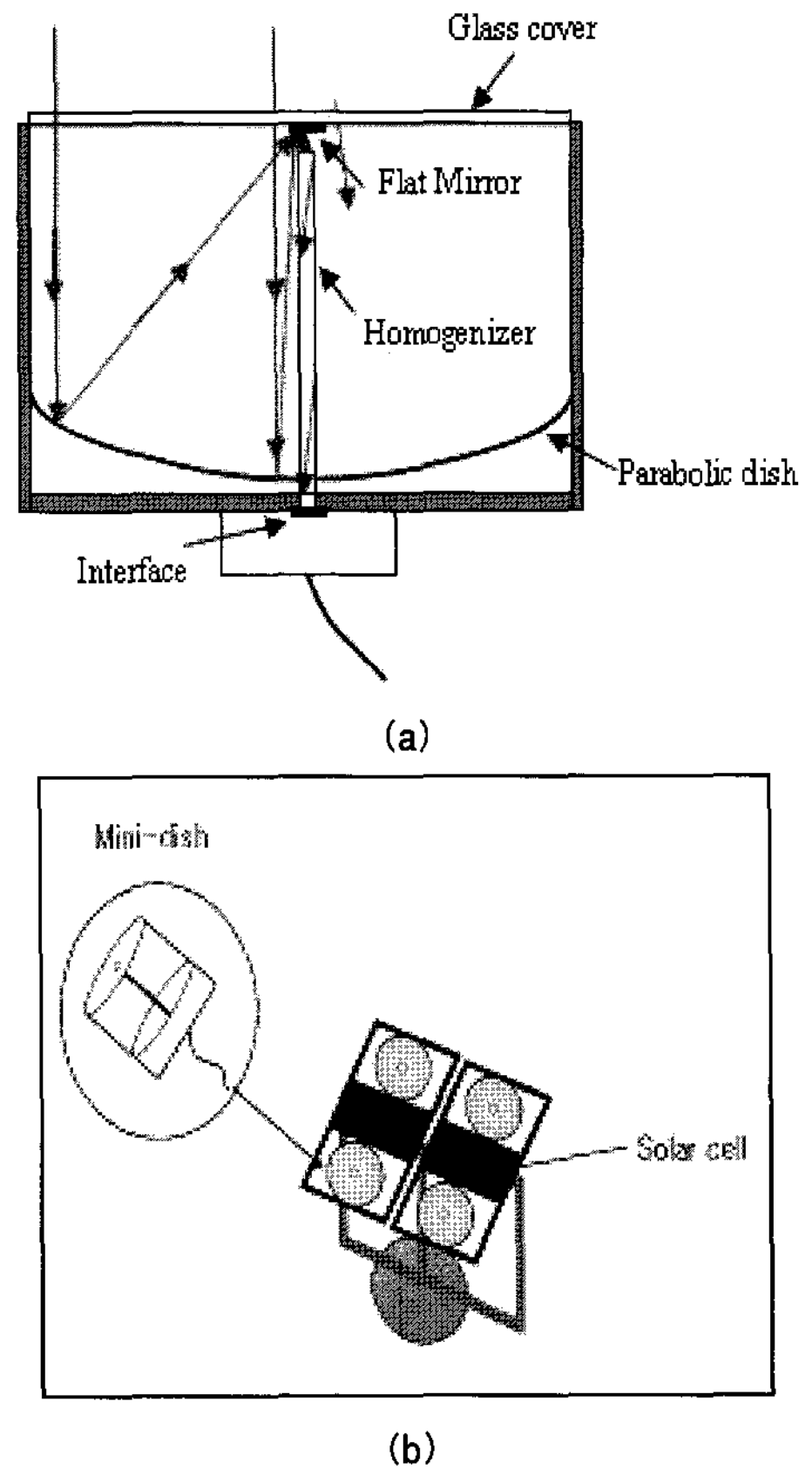


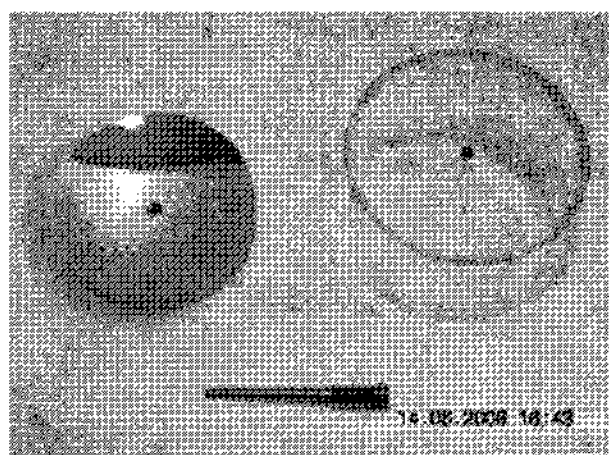
Fig. 1 Design concept of the solar concentrator:
(a) reflector unit (b) total assembly

Fig. 1 shows the design concept of the system investigated in the present work. Here, every component used is amenable to mass production process making the unit cost as low as possible. Especially, apart from existing systems, an adaptor of multiple output energy modes has been designed and connected to the input and output end of the optic fiber. It allows the solar energy coming out from the homogenizer tube and from the optic fiber to be converted to different energy forms for illumination or other applications (Korea patent application 2007-20366).

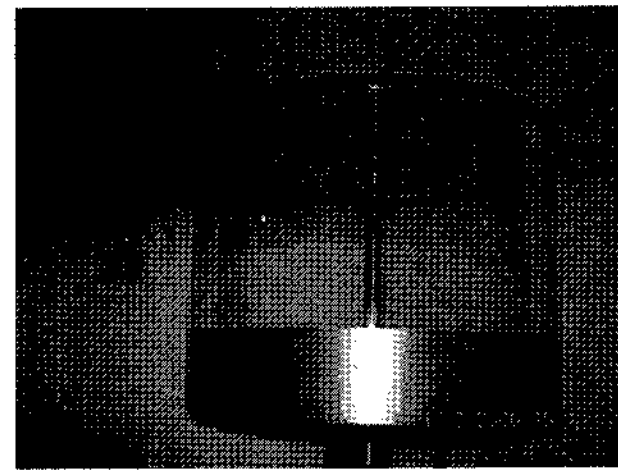
2.3 Fabrication

The mini-dish aforementioned is prepared by cutting an aluminum block on a CNC milling machine. Its diameter is 25cm 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 fibre bundles of 5m in length. When a flat mirror used as the 2nd reflection mirror, the homogenizer is made with a tapered stainless steel pipe 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 piece of round mirror of 15mm 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 when observations are made to check its performance in concentrating sun rays onto the small opening of the homogenizer via mirror.



(a) major parts



(b) assembled

Fig. 2 A mini-dish reflector unit

To elicit the most effective way to collect and transmit sunlight to the designated position, two 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 as shown in Fig. 3 (b).

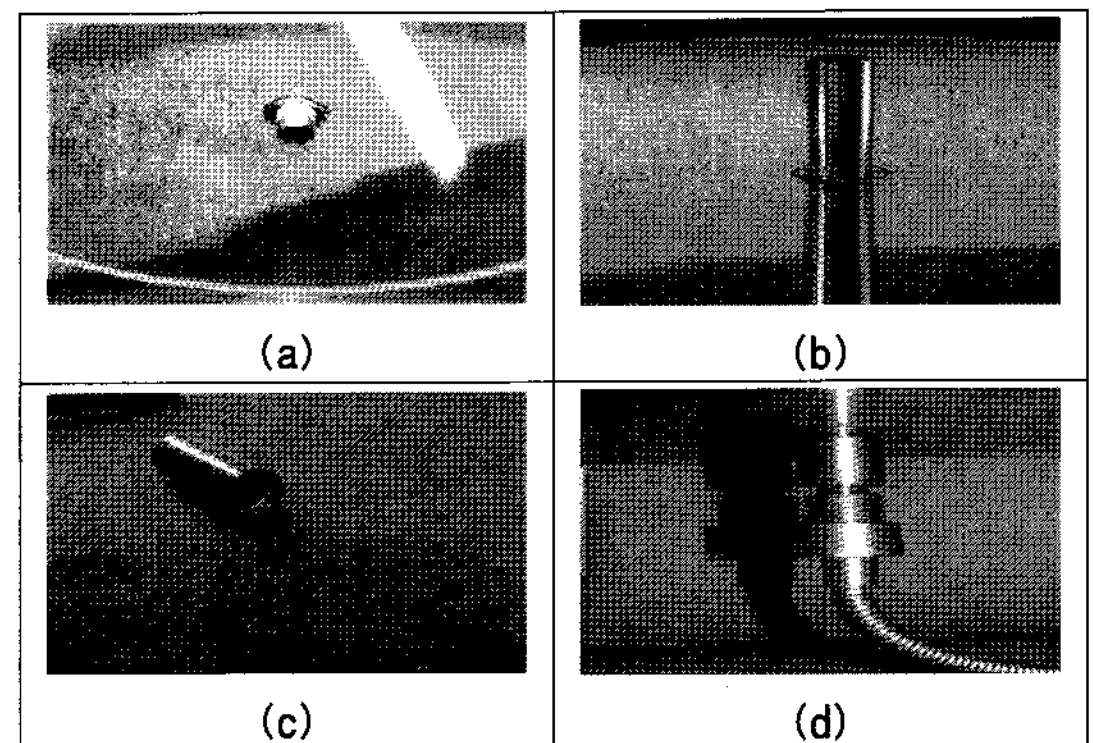


Fig. 3 Major components tested :
 (a) convex 2nd mirror, (b) homogenizer,
 (c) convex lens, (d) optical fibre cord

A convex lens, Fig. 3(c), was inserted near the lower end of the homogenizer for the latter to focus down streaming sunlight into the end of a fibre optic receiver. This facilitates the use of smaller optical fibre

bundles regardless of the size of the homogenizer pipe.

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 although it is not feasible anyway as incoming sun rays get blocked at the center. A concave mirror instead facilitates the use of a shorter and larger (in diameter) homogenizer. This, however, calls for a very precise positioning of the mirror and an utmost care should be exercised in this regard.

3. PERFORMANCE PREDICTION

Several alternatives were considered, including OPTICAD and TracePro™. Photopia (Lighting Technologies Inc, 2005) was chosen to perform all ray tracing simulations⁷⁾, as it was capable of importing CAD object files (Rhinoceros), and the availability of required technical information and general assistance.

The majority of modern ray tracing-based analysis tools use the Monte-Carlo method to solve the coupled integral differential equations used to calculate the illuminance distributions in 3D models.

Photopia differs from other commercially available packages in that it can cope with the high number of reflections that occur within internally reflecting daylighting systems^{5), 6)}. This feature is, especially, useful in modelling our system as a myriad

number of reflections take place inside the homogenizer, let alone the optical fibre bundles.

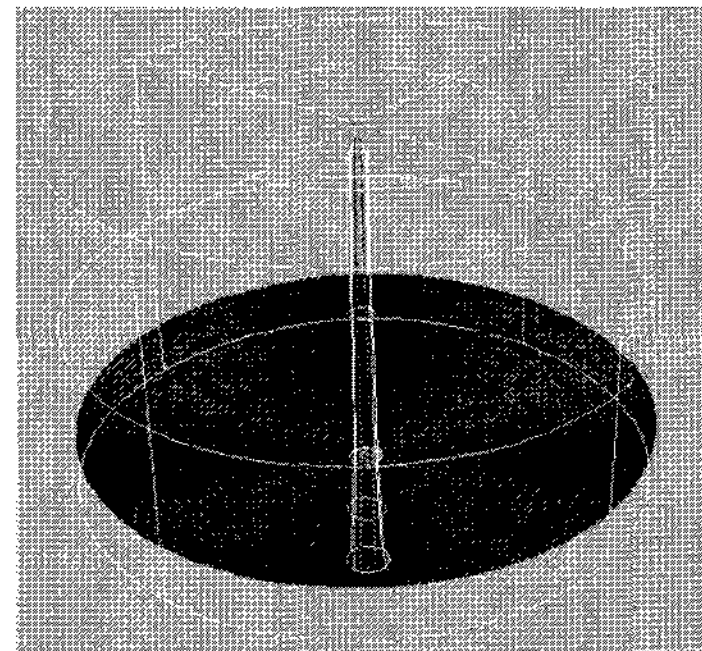


Fig. 4. 3D modelling by Rhinoceros

Fig. 4 shows the 3D modelling of the mini-dish reflector unit prepared by Rhinoceros, which is imported by Photopia for 3D performance analysis.

Rhinoceros is a stand-alone, commercial NURBS-based modeling tool equipped with a very convenient user interface. Especially, when compared to AutoCAD, it is quite intuitive and makes great use of the mouse.

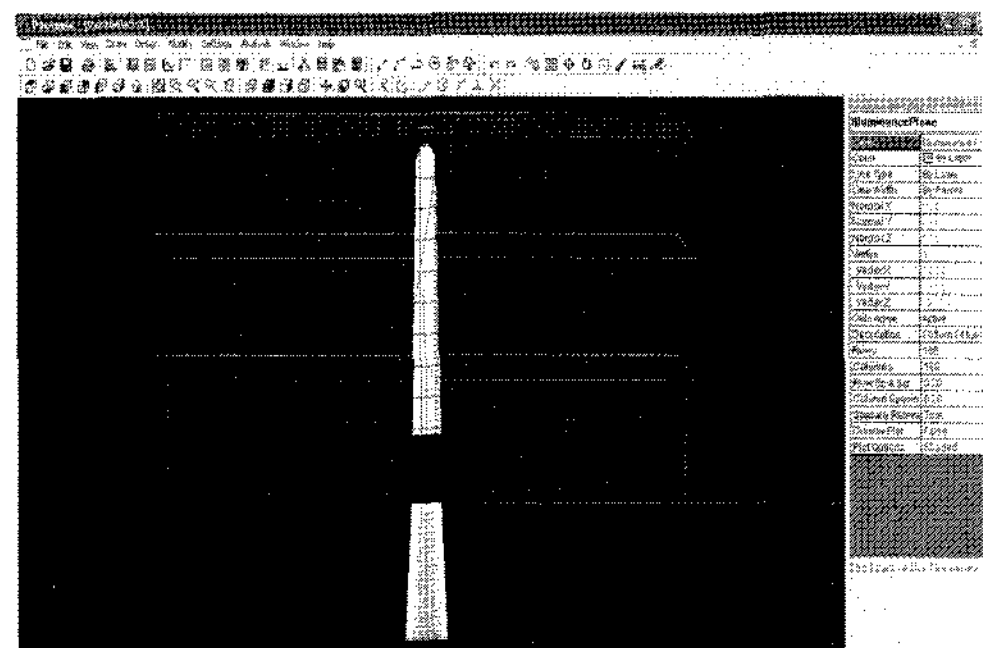


Fig. 5 Imported by Photopia

Table 1 summarizes the optical properties of the major components. A clear sky condition is assumed throughout the analysis.

The optical properties of the virtual objects are defined as reflective, transmissive or refractive. Materials are assigned to those objects, the properties of each material coming from a database of material optical properties.

Table 1: Material optical properties

Material	Property value
Mirror reflectance	99% specular
Homogenizer outer reflectance	95% specular
Homogenizer inner reflectance	98% specular
Dish	95% specular
Acrylic case	92% transmitting

Fig. 6 shows a model close-up of the homogenizer tip in Photopia. As can be seen, the homogenizer tip and the 2nd reflecting mirror are very closely located as aforementioned.

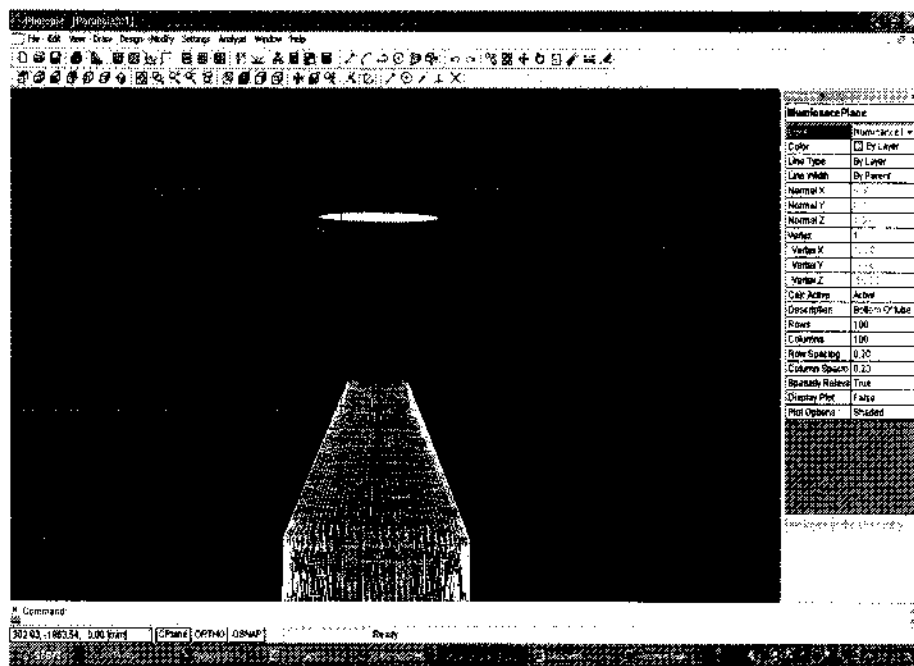


Fig. 6 Model close-up of homogenizer tip in Photopia.

To test if all of the light concentrated by the parabolic dish is captured by the system, the total reflected illuminance directly above the dish concentrator is measured. Here, the illuminance plane is

positioned just above the reflecting mirror facing down. The shaded area in Fig. 7 shows that the dish reflector is concentrating light as expected and a proportion of the reflected light bypasses the mirror and escaping around the edges. The black disk in the centre of the image is the shadow cast by the mirror.

A number of different parabolic profiles in designing the dish reflector could be tested to elicit the most effective and feasible design allowing most of the impinging solar rays on the dish reflector to be transmitted to the homogenizer tube. The mini-dish reflector shown in Fig. 2 is prepared by such design process.

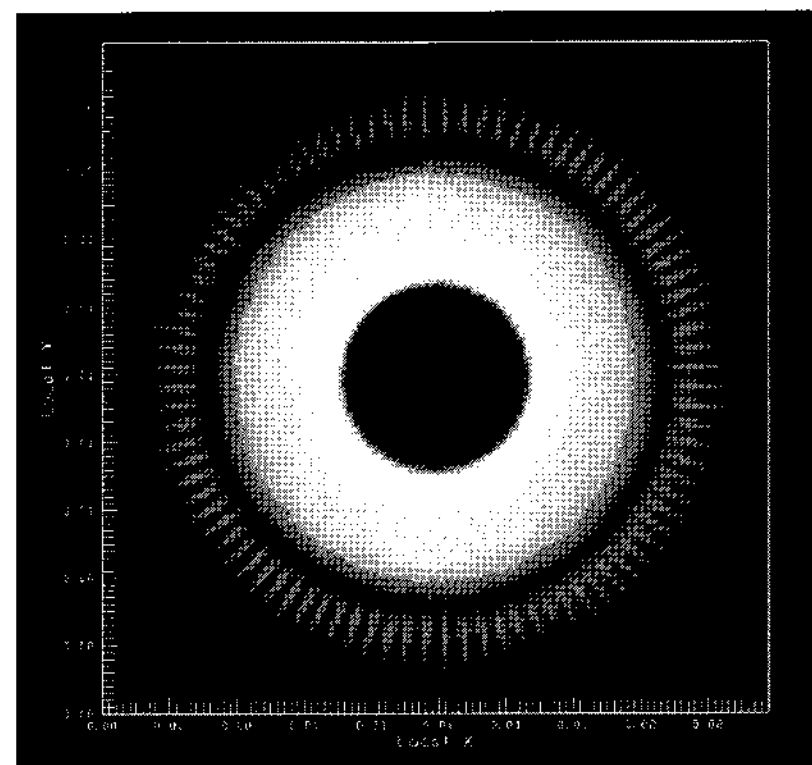


Fig. 7 Total reflected illuminance measured directly above the dish concentrator.

Fig. 8 shows the illuminance distribution just below the rim of the homogenizer opening : the illuminance plane is positioned within the homogenizer. This is useful to test whether the light reflected by the mirror does get sent down the homogenizer. The bright area centred in the middle of the shaded plot confirms that all the light

reflected from the mirror will enter the homogenizer.

When designing the 2nd reflecting mirrors of different shapes, this stage of simulation was proven to be very effective in assessing their performance as the shaded plot vividly shows it all.

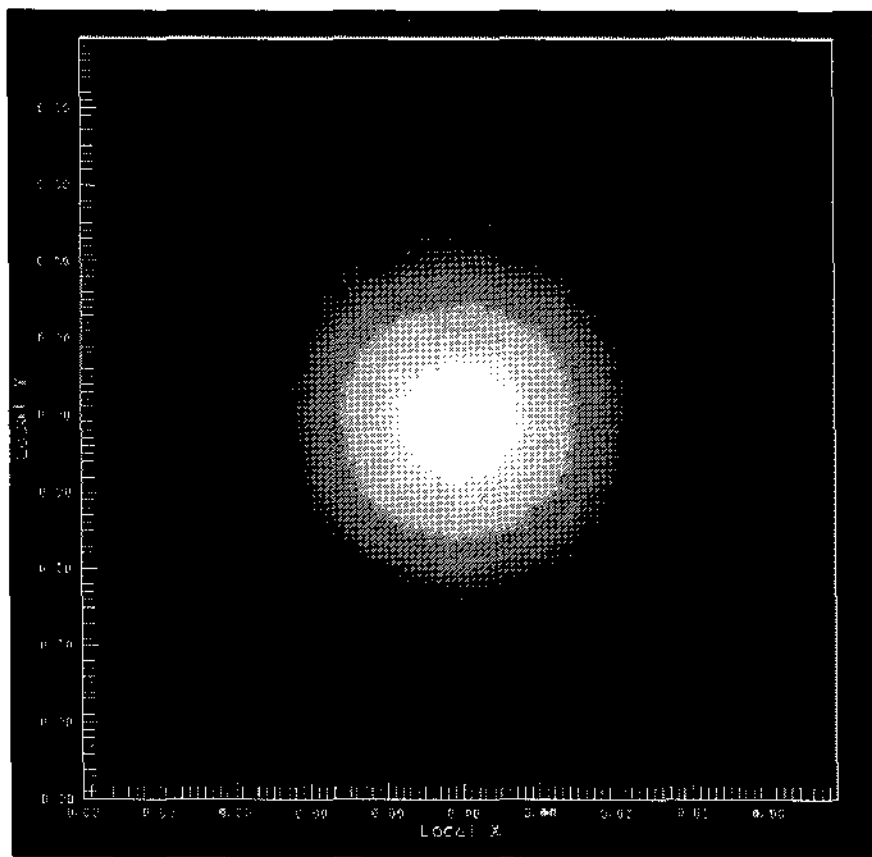


Fig. 8 Illuminance distribution homogenizer opening

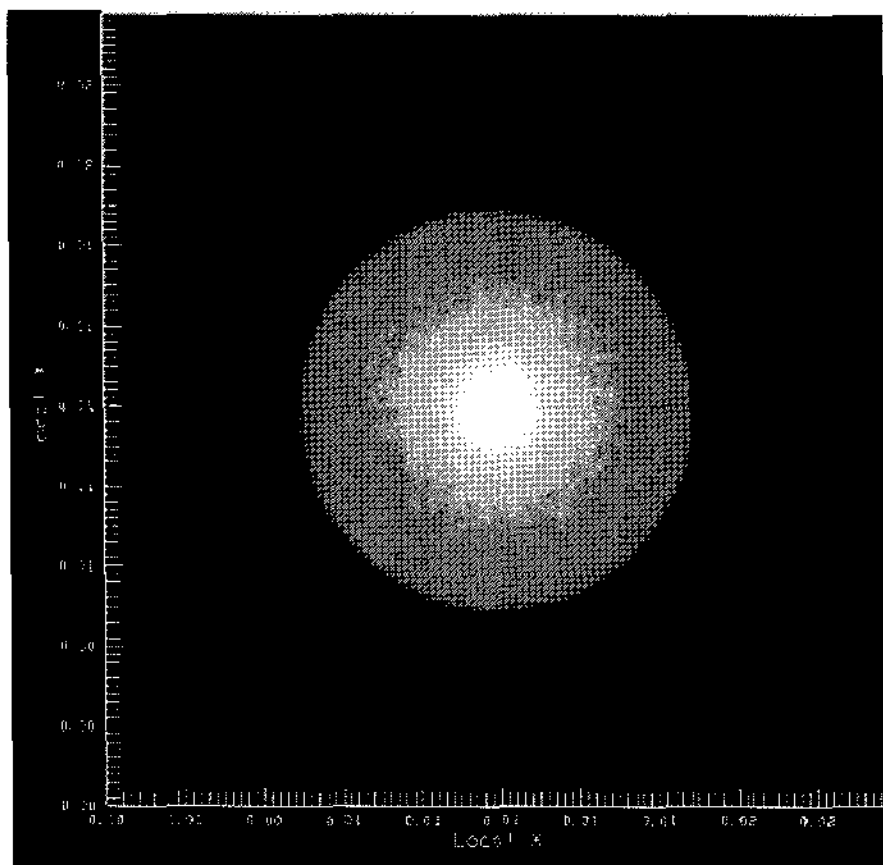


Fig. 9 Illuminance distribution bottom of tube

Fig. 9 gives the illuminance distribution at the bottom of the homogenizer. As shown, the brightest area is located at the center which indicates the homogenizer is

transmitting light as expected. Fig. 10 is a contour plot of the illuminance distribution at the homogenizer bottom(exit), which shows an increase in its intensity toward the centre of the homogenizer. If the light is dispersed at the exit, it could make a luminaire of 1,145 lumens. This is comparable to our former experimental results and other commercially available daylighting systems with similar solar collector area, where total luminous fluxes of 1,040~1,280 lumens were measured⁸⁾. Of course, these data are subject to change according to the sky condition used for simulation.

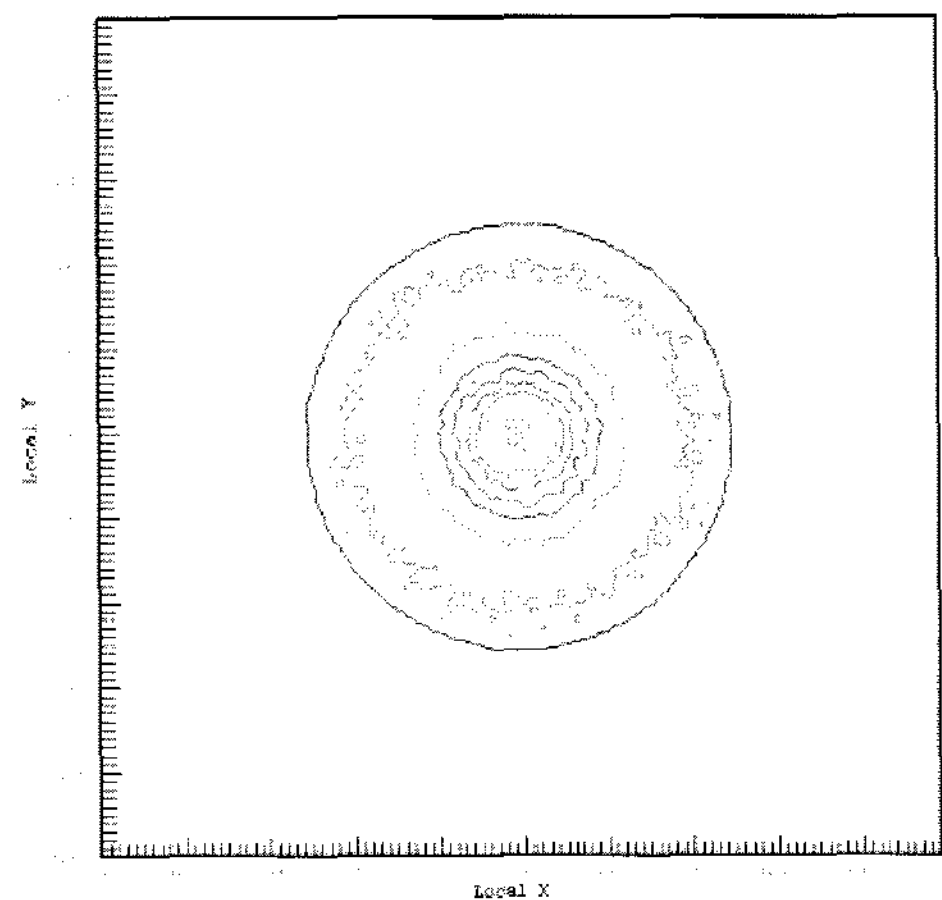


Fig. 10 Contour plot of illuminance distribution homogenizer exit. Clustering of circular contours at the centre exhibit high density solar flux.

4. CONCLUSIONS

A solar tracking fibre optic concentrator system for daylighting has been designed, fabricated and analyzed for its application in reality. To elicit the most feasible

model, a number of options are tested for the 2nd reflection mirror. Especially, a forward ray tracing software package, Photopia, is employed to simulate light intensity and its distribution at various locations within major components of the system when a flat mirror is used as the 2nd reflection mirror. It turned out that this type of simulation offers the experimenter to “see” and “quantify” illuminance levels that would be very difficult to measure experimentally and the act of measurement itself would invalidate the results by creating shadows. Also, it allows some design factors such as the shape of the parabolic dish or the size and shape of the reflecting mirror to be tested and analyzed without undue difficulties.

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