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A new type of daylight passive collector: The shaped refractor

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In order to satisfy the requirements of energy-saving and lighting comfort in places which have no direct access to daylight through windows, it is possible to set up an optical rod daylighting system. However, there is no information as to how efficient such a system might be for the passive collection of daylight. This paper explores the possibility of increasing the passive collection of daylight through modifications to the shape of the acrylic rod at the collection area. As a result, an equation for the calculation of a shape that optimises the passive collection of daylight through refraction into the optical rod is developed. The shape depends on the latitude where the system is installed.

1. Introduction

The environmental crisis our planet is facing has generated an exceptional interest in the reasonable use of non-renewable energies and a greater spread and better use of renewable ones. Recently, international organisations such as the UN have declared it a priority to diminish fossil fuel consumption and decrease greenhouse gas emissions, both vital actions in the fight against global warming.[1] These objectives can be achieved, partly, by increasing the use of daylight for the lighting of interiors. During daytime hours it would be possible to minimise and in some cases even do without electric lighting. It is estimated that this could lead to a 32% saving in energy consumption.[2] Another advantage is that users of workplaces, such as factories and offices, have generally expressed a strong preference for daylight over artificial light in their interiors.[3]

For internal windowless places with no direct access to daylight to meet the requirements of energy-saving and lighting comfort, it is valid to suggest the installation of some form of light guide system. Within this category we find optical rods. These rods are of special interest because they are considered to be a useful mix between the versatility of optical fibre system installations and the performance of mirror light pipes.[4]

Light guide systems are composed generally of three elements which are differentiated according to their function: A collector, a transport section and a means of emitting the light. Among the most used collector elements we can find parabolic concentrators,[5] Fresnel lenses,[6] light redirecting systems by rotating flat mirrors,[7] heliostats[8] and simply translucent protective domes.[9] Each of these elements can be connected to a system that automates the movement of the reception surface (by software-controlled electromechanical means) so as to follow the course of the sun and hence to maximise the amount of the light collected throughout the day.[10]

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However, there is no investigation, yet, as to which of the different existing types of collection element is most efficient for daylight collection by the optical rod system. This is a problem because one of the main obstacles to the spread of the use of optical rod daylighting systems is the lack of photometric data about them. This makes it difficult to predict their lighting performance and at the same time it causes uncertainty and a lack of precision when planning the installation of such a technology.[11]

Optical rods have another advantage over many of the other light guide systems. They are simple to make, install and maintain. Many countries do not have the technological capacity to produce automated daylight collection devices[12] due to both the cost of production and the programming and later maintenance of the control software required for their operation. Therefore, the aim of this paper is to explore the potential to optimise passive daylight collection with optical rods by modifying the shape of the acrylic material in its collection area so as to determine the amount of light feasibly getting into an interior space located under clear skies.[13]

2. Materials and methods

Out of the total rod length (1200 mm) and diameter (25 mm), the collection area was defined as the part of polymethyl methacrylate (PMMA) material located outside the interior's ceiling structure, more specifically, the area of the rod exposed to direct and diffuse radiation from the sky (Figure 1).

To determine the collection efficiency of differently shaped collection areas, the luminous flux (lm) was measured as that emitted from the area of the rod at the transition between the exterior space and the interior (Figure 2).

The choice of this section through the optical rod is based on the fact that this circumference corresponds to the maximum surface for passage of light from the collection area to the transport area of the rod, regardless of any possible change of the exterior area which is exposed to the sky.

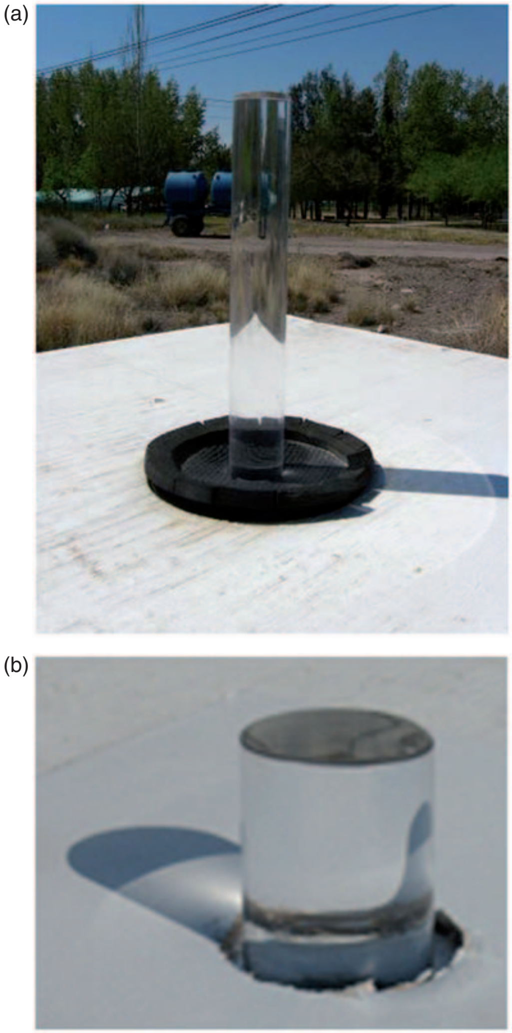


Figure 1 The collector area: Area of the optical rod exposed to direct and diffuse radiation

A measuring device was used to measure the luminous intensity distribution of the optical rod based on the design of a bidirectional goniophotometer and consisting of a cube of 600 mm side. The interior surfaces of this cube were painted matte black so as to

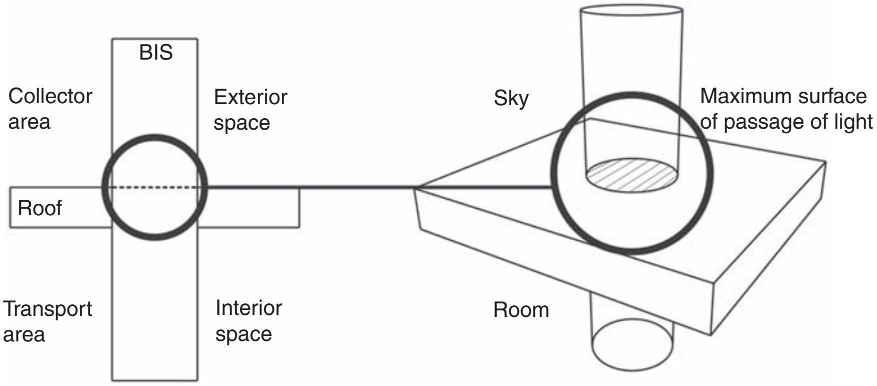


Figure 2 The maximum surface of passage of light from the collector area to the transport area of the rod

minimise the reflections inside the cube. The dimensions of the cube were determined by the rule that states that in order to consider the optical rod a point source, the emitting area must be five times smaller than the measurement distance.

The sensors used to measure the illuminance at seven points on a semicircular arc comprised seven International Light SCD110 detectors which were linked to a IL1700 multichannel data acquisition system and connected to a Pentium IV computer for data storage. The illuminances, recorded in lux, were later transformed to luminous intensities by the application of the inverse-square law of distance through the following equation:

$$I = \frac{E \cdot d^2}{\cos \gamma}, \tag{1}$$

where I is the luminous intensity in candelas, E the illuminance in lux, d the distance from the source to the measuring point (m) and cos γ the cosine of the elevation angle.

Next, the luminous intensity values were processed using the Photometric Tool Box software, resulting in a graphical and digital polar curve in the format developed by the Illuminating Engineering Society of North America. Finally, the luminous intensity distribution was used to calculate the luminous flux of the light source. In order to carry out this calculation a $1\,\mathrm{m} \times 1\,\mathrm{m} \times 1\,\mathrm{m}$ virtual space was created in RELUX software and the illuminance produced by the source over every interior surface was calculated excluding the interreflected parts. Thus, the luminous flux reaching each interior surface of the cube was calculated as the product of average illuminance times the area of each wall, the expression of which being:

$$\begin{aligned}\Phi_{lum} &= E_1 \cdot A_1 + E_2 \cdot A_2 + \cdots + E_6 \cdot A_6 \\ &= A \cdot \sum_1^6 E_i,\end{aligned} \tag{2}$$

where A is the area of each virtual wall (m^2) and E_i, $i = 1 \ldots 6$ the average illuminance on each of the box walls (lx).

Using this method, the luminous flux produced by different designs of collector was studied. The luminous flux admitted through the entrance area without a rod was also studied. This case was taken as a reference and is referred to as the pattern hole condition.

3. Tests on the shape of the collector

First, different shapes for the end of the optical rods were created from surfaces of revolution. In all, six different collection shapes, created through lathe shaping and later polishing, so as to obtain a mirror polished finish of the pieces, were examined (Figure 3). These shapes were designed according to the premise of following the path of the sun and its geometry. This is why flat surfaces with some degree of slope were not used but rather shapes based on surfaces of revolution. The measurements were made during the months of April, July and October 2007 and January 2008. Each shaped collector was evaluated over five consecutive days, after a prior assessment of the levels of luminous flux achieved by the pattern hole condition during a period of twenty-four hours under clear sky conditions.

The length of the experiment for the six different rod shapes comprised a period of about 30 days (from 28th May to 24th June 2007). Although it is true to say that it was necessary to take into account some changes in the luminous climate, since the Sun reduced its height day by day, it was considered very valuable to obtain that data under real daylight conditions. This way, the differences observed in the daily performance of each shape showed that the shaping of the collection area did, indeed, modify the performance of the optical rod system.

The results obtained, shown in Figures 4–6, demonstrate the differences in the amount of luminous flux collected for the different shaped rods. The first thing to note about these figures are the five curves with their peaks corresponding to the daily highest solar elevation hours, which coincide with the moments of highest daylight power in days with clear sky conditions. Night hours were omitted from the graph for the easier viewing of the information. The luminous flux values shown in Figures 4–6 are for five-minute records taken throughout the daytime sunshine period between 08.30 and 18.00 hours.

4. Results

The first shape to consider is that of the pattern rod. This curve shows the variation of

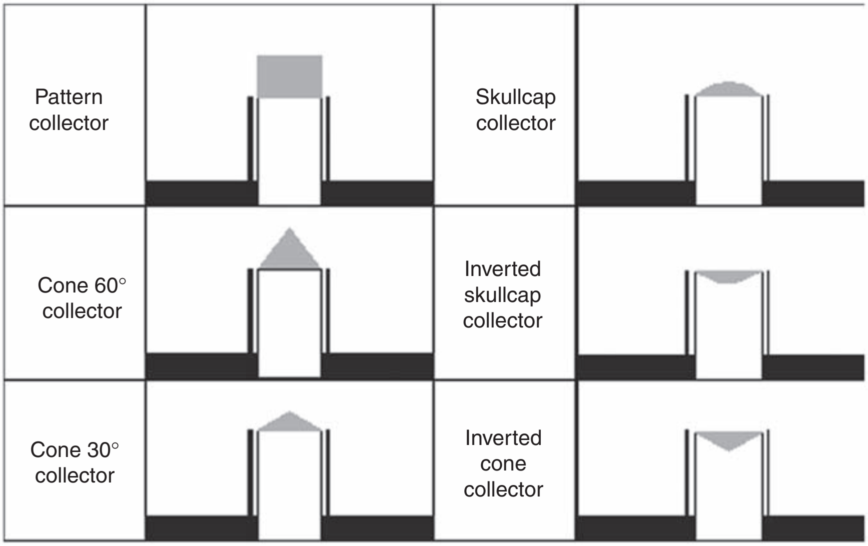


Figure 3 Schematic diagrams of the tested shapes

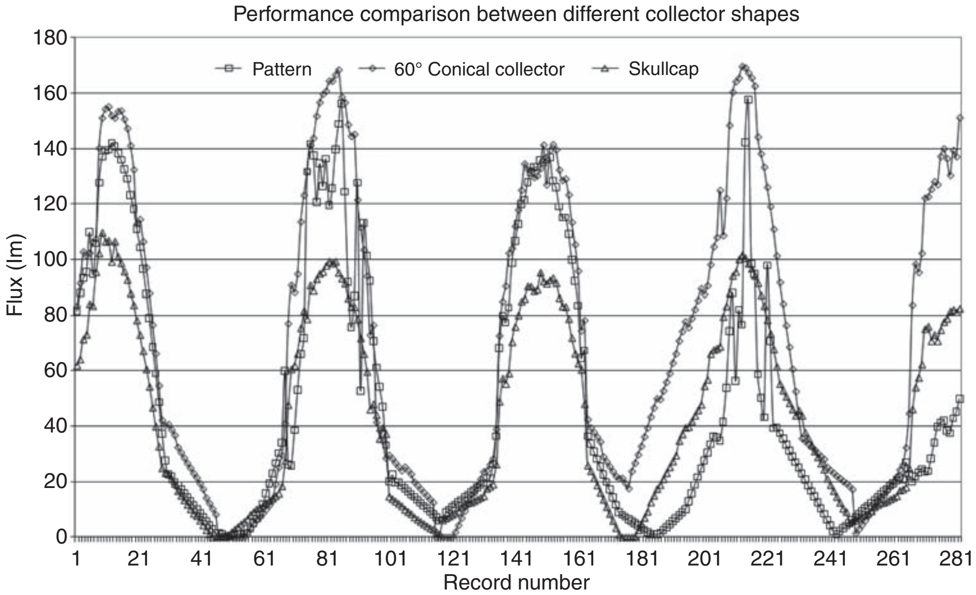


Figure 4 Luminous flux delivered by the pattern, 60° conical collector and skullcap shapes

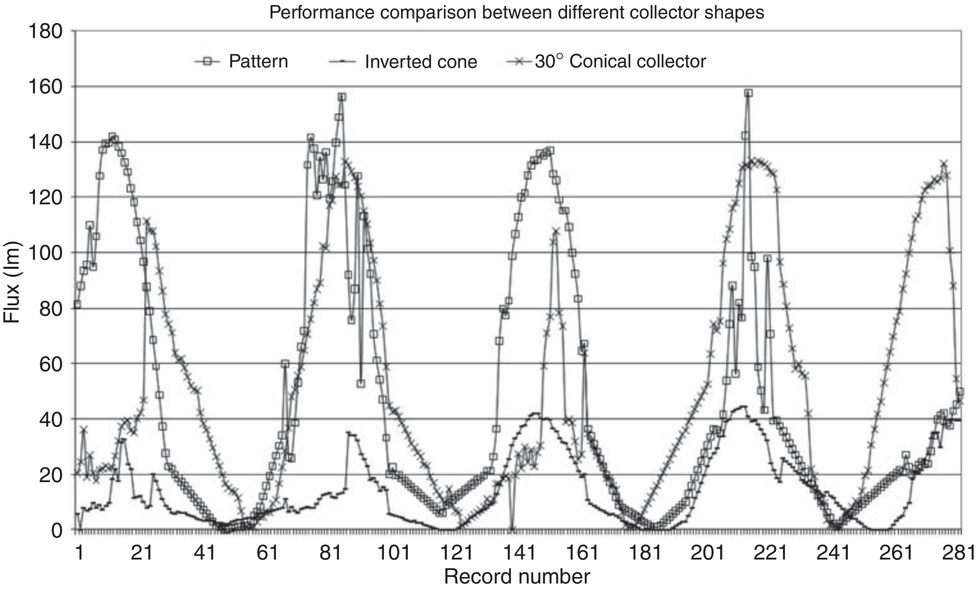


Figure 5 Luminous flux delivered by the pattern, inverted cone and 30° conical collector shapes

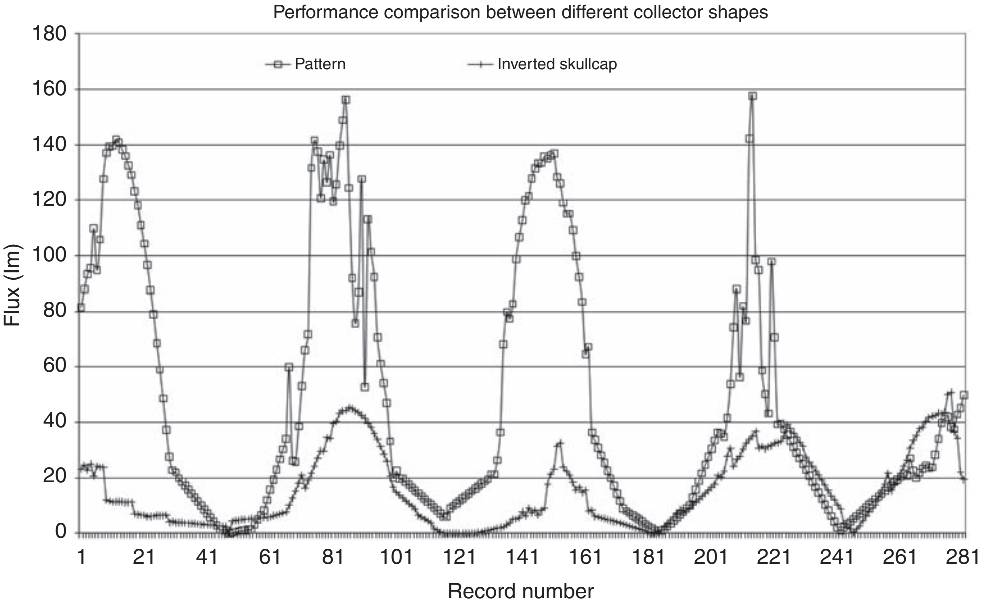


Figure 6 Luminous flux delivered by the pattern and inverted skullcap shapes

the daily luminous flux that the rod could collect with the conventional shape.

The measurements for the 60° conical collector shape started the series of tests on the modified rods. It was possible to observe in the first place that the curve corresponding to this shape follows the curve of the pattern rod, both in the peaks and falls. However, and despite the fact that the data gathering was carried out 5 days closer to the start of the winter season, the outline of the curve was slightly higher than the one of the pattern rod. Examination of the data, carried out through a percentage comparison of every point of the information, showed an average 9% increase in luminous flux for the 60° conical collector.

The next shape under study is the skullcap collector. It is possible to observe at first glance that the performances achieved with this shape were lower than those registered for the two previous cases. It is also possible to see that it reproduced the curve of the pattern rod although a comparison at every point showed that the luminous flux only achieved an average of 70% of the levels collected by the pattern rod.

The next shape under test is the inverted cone. In this case an abrupt fall in the luminous flux is obvious. This result confirmed experimentally a fact that had been raising doubts about the validity of the suggested hypothesis: It was proved that the shaping could have a strong effect on the lighting performance of the optical rods. In addition to this, examination of the curve showed that the match to the pattern rod results was worse when using this shape. Thus, the inverted cone shape only achieved 30% of the luminous flux achieved by the pattern shape. Nevertheless, the uniformity of the luminous flux collected by the inverted cone rod throughout the day improved significantly, increasing the mean/maximum ratio from 0.23 to 0.45.

During the test of the 30° cone shape it was possible to identify once more luminous flux levels close to those achieved by the pattern shape. Despite the fact that the test of every point showed a comparative performance of about 90%, the closeness of the records in time made it hard to determine whether these results were due to the shape under test or produced by a natural reduction of the available global flux at that moment.

Finally, the records for the inverted skull-cap collector shape showed a similar form to those of the inverted cone. Indeed, the comparative levels for each point showed a fall of around 80% compared to the pattern shape and, in addition to this; it was possible to confirm the increase of the uniformity by a look at the graph and its lack of high peaks and falls which is the characteristic of the lighting behaviour of the daily solar resource.

5. The basis of a model

Having confirmed that the shaping of the plastic material in the collection area modifies the performance of the optical rod daylighting system, it was decided to develop an equation to allow the calculation of the angles of slope of the acrylic surface that were necessary for refracting the incident rays from 0° of solar elevation upwards to an angle contained within the critical angle which is determined by the ratio of refractive indices of the materials.

In this ratio of refractive indices – for our case both the one of the PMMA acrylic and that of the air – there is an angle, from the perpendicular, in which the ray grazes the surface of the material, and it is observed that after that the beam of light stays inside the material. These principles of reflection of light described by Snell can be expressed through the following equation[14]:

$$n_1 \times \sin\varphi_1 = n_2 \times \sin\varphi_2, \tag{3}$$

where n_1 is the refractive index of the medium 1, in this case, air; sin φ_1 the sine of the angle of incidence of the ray onto the material; n_2 the refractive index of the medium 2, in this case, PMMA and sin φ_2 the sine of the angle refracted within the material.

In addition to this, the variables associated with solar geometry were considered, since the functioning of the optical rods would rely on them. Considering that within the sun path, March 21 and September 21 are characterised by having at solar noon an azimuth equal to zero, this means that the sun and the zenith form an angle which is equal to latitude j, so that it is possible to calculate the solar altitude (A) as

$$A = 90 - j. \tag{4}$$

In the same way, the 21st December sun path (summer solstice in the Southern hemisphere) is peculiar given that when the sun is over the southern hemisphere at noon time, it forms with the zenith an angle which is equal to latitude j minus the declination($d = 23.5°$) so that the solar altitude can be calculated the following way: $A = 90 - j + 23.5°$.

Conversely, during winter solstice (21 June), the sun path is characterised by showing at noon an angle formed by the sun and the zenith which is equal to latitude j plus the declination ($d = 23.5°$), so that the solar altitude can be calculated the following way: $A = 90 - j - 23.5°$.

Daytime sun paths can be simplified by considering them as perfect circles, the axes of which coincide with the Earth's axis, covering 360° in 24 h and having each hour a time angle equal to 15°.

6. An analytical model

The development of the analytical model started from the determination of the value of the critical angle for the acrylic–air coupling. This is given by:

$$\theta_{mat} = \arcsin(n_1/n_2), \tag{5}$$

where θ_{mat} is the critical angle for the air–PMMA coupling; n_1 is the refractive index of air and n_2 is the refractive index of acrylic.

After having stated that this was the angle where refraction was produced at the limit of the interface between the surfaces and following Snell's law:

$$n_1 \times \sin\varphi_1 = n_2 \times \sin\theta_{mat}, \tag{6}$$

Then:

$$\begin{aligned} n_1 \times \sin\varphi_1 &= n_2 \times \sin(\arcsin n_1/n_2), \\ n_1 \times \sin\varphi_1 &= n_2 \times (n_1/n_2), \\ \sin\varphi_1 &= 1. \end{aligned} \tag{7}$$

Next, we incorporated the equations related to solar altitude $\Phi_{\max}$ which enabled us to deduce what would be the inclinations that the surface of the material should adopt so that the deviation of the refracted rays from the normal axis approach the critical angle, resulting in:

$$\Phi_{\max} = 90 - j \pm 23.5.$$

So:

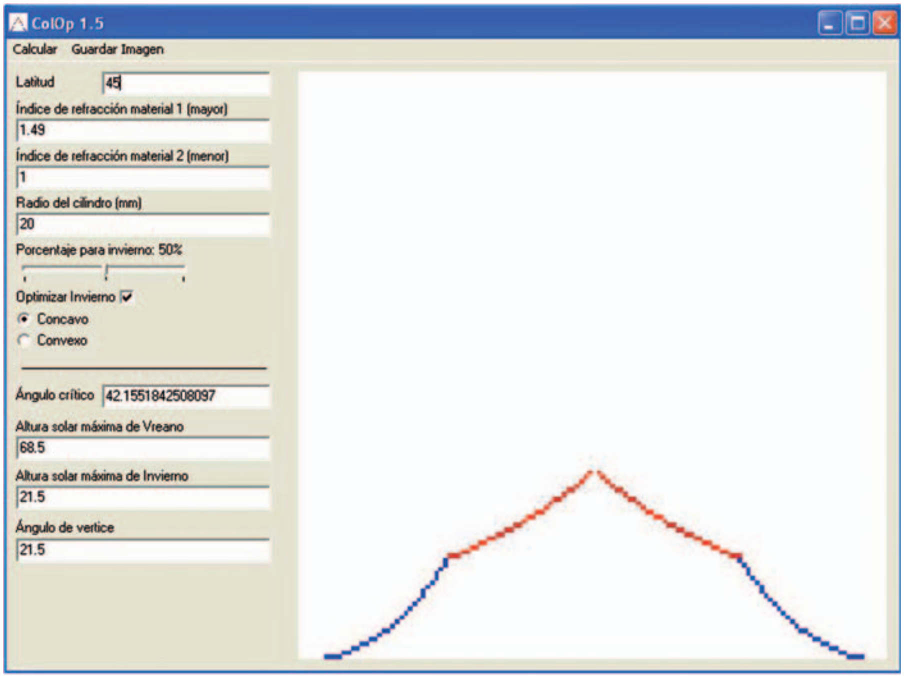
$$\varphi_a = \Phi_{\max} + \gamma, \tag{8}$$

where φ_a is the angle of incidence of the ray over the surface in the acrylic material; $\Phi_{\max}$ the angle of the maximum solar altitude reached at the winter and summer solstices and γ the angle of inclination from the normal of the surface of the acrylic material where the incident ray falls.

Placing Equation (8) in Equation (7):

$$\begin{aligned} \sin(\Phi_{\max} + \gamma) &= 1, \\ \Phi_{\max} + \gamma &= \arcsin 1 = 90^\circ, \\ \gamma &= 90^\circ - \Phi_{\max}. \end{aligned} \tag{9}$$

Following this reasoning it was determined that the angle of inclination γ from the normal axis that the surface of the material exposed to incident rays had to acquire was equal to the difference between 90° and the maximum altitude angle reached by the sun at



Latitud: 45

Índice de refracción material 1 (mayor): 1.49

Índice de refracción material 2 (menor): 1

Radio del cilindro (mm): 20

Porcentaje para invierno: 50%

Optimizar Invierno ☑

● Concavo

○ Convexo

Ángulo crítico: 42.1551842508097

Altura solar máxima de Vreano: 68.5

Altura solar máxima de Invierno: 21.5

Ángulo de vertice: 21.5

Figure 7 Outline obtained for a shaped refractive collector located at latitude 33°32″

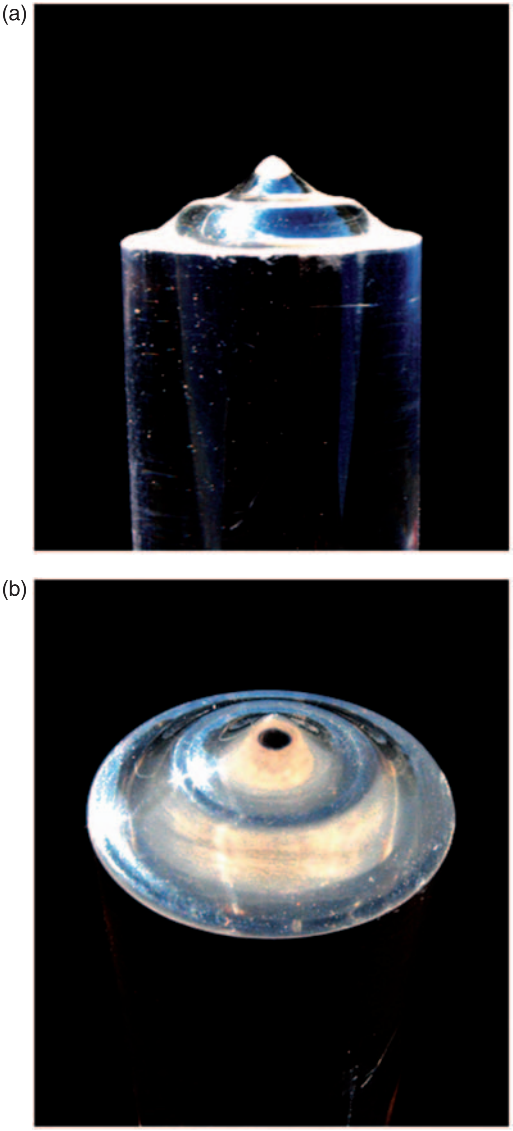


Figure 8 Two views of an acrylic piece turned so as to produce the optimised outline

the summer and winter solstices, depending on the latitude where the optical rod daylighting system is installed.

7. Application of the model

Equation (9) was transferred to a software (developed in Delphi language) that made it possible to build a graphic outline which would correspond to the angles obtained for each solar altitude, going from 0°, which would be close to sunrise, up to the maximum possible altitude the sun could reach depending on the geographic latitude.

The data entered in the software correspond to the latitude of the place where the rods are installed, the refractive indices of the translucent media and the diameter of the cylindrical section of the rod, expressed in millimetres. The software delivers the following outputs: The value of the critical angle for total internal reflection, the maximum solar altitude reached at the summer and winter solstices, the value in degrees of the angle that forms the upper vertex of the outline and the graphic outline corresponding to surface of revolution needed for an optimum collector (Figure 7).

In order to test the best possible performance of the profile obtained for the latitude of Mendoza, Argentina, an acrylic piece that reproduced the optimum outline was made (Figure 8).

Measurements were made for the 15 and 30 July 2008, with records every 15 minutes, with the aim of evaluating the lighting performance of the conventional pattern shape and contrasting it with the performance of the software-optimised shape. The results obtained for a representative day are depicted in Figure 9. The curves show that the computer-optimised shape of the collector mainly affected the performance of the collector during the hours when the sun was low in the sky. The application of the optimised outline inverted the curve of the pattern performance, producing an elevation of the extremes of the efficiency line which coincided with twilight and sunset, while it also generated a fall in the central area which corresponded to solar noon. A comparison of every point of both curves showed that the luminous flux of the optimised shape was, on average, 315% higher than that of the pattern shape.

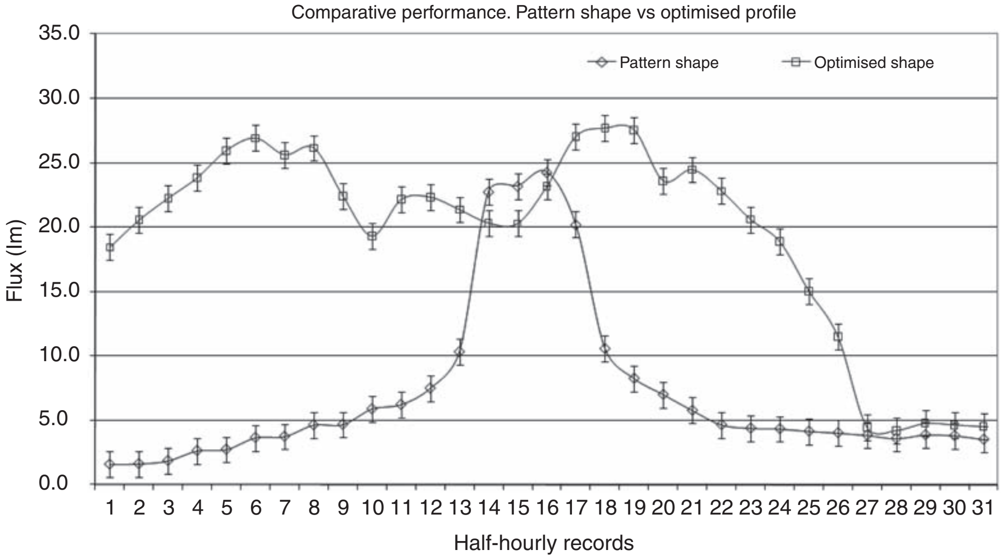


Figure 9 Luminous flux delivered by an optical rod with the optimised shape and with the pattern shape over 16 hours on 16 July 2008

8. Conclusions

The experiments carried out showed that it is possible to modify the characteristics of the optical rod's performance by modifying the shape of the acrylic material in the collection area. This offered the possibility of increasing the performance of optical rods by designing a shape profile which would be made of the same PMMA material as the rod. Using the concepts of refraction and total internal reflection, an equation has been developed that will help to generate an outline of a surface of revolution that, once it is applied at the collection area of the optical rods, will optimise the passive collection of daylight for vertical rod systems.

This equation produces the values of the angles of inclination from the normal that the acrylic material should have for the incident rays to be refracted internally and kept within the acceptance cone of the optical rods. Using this, we were able to generate a new type of shaped collector element, a passive daylight collector using refraction.

The test of this shaped refractive collector's performance showed that the luminous flux collected markedly increased over that of the conventional pattern shape, as well as widening the daylight collection time slot.

Acknowledgements

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