Ray tracing study for non-imaging daylight collectors

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Abstract

This paper presents a novel method to study how well non-imaging daylight collectors pipe diffuse daylight into long horizontal funnels for illuminating deep buildings. Forward ray tracing is used to derive luminous intensity distributions curves (LIDC) of such collectors centered in an arc-shaped light source representing daylight. New photometric characteristics such as 2D flux, angular spread and horizontal offset are introduced as a function of such LIDC. They are applied for quantifying and thus comparing different collector contours.

Keywords: Non-imaging daylight collectors; Performance criteria; Anidolic; Photometry; Forward ray tracing

1. Introduction

Non-imaging collectors are typically used to concentrate light through parabolic or elliptical mirrors. Compound parabolic collectors are widely used to concentrate sunlight for solar thermal applications (Hsieh, 1979; Winston, 1974; Rabl, 1976a,b; Eames, 1993; Welford and Winston, 1989). In buildings, anidolic (from Greek \textit{an}: non and \textit{eidolon}: image) daylight collectors can be used to collect and collimate daylight for efficient transportation into deep buildings zones. They can be part of integrated systems as shown in Fig. 1. Here, the collector is located at the building’s façade or roof and is connected to a horizontal or vertical pipe for efficient transport of light over long distances with diffusers to divert light into spaces that require light. These systems provide natural light well beyond the reach of conventional windows (Courret et al., 1998; Scartezzini and Courret, 2002; Compagnon et al., 1993). Their application in the tropics with bright zenithal skylight is promising (Wittkopf et al., 2006; Wittkopf, 2007; Lau et al., 2007).

2. Problem statement

Despite such promising experiments, integration of such systems into buildings is not widespread. Besides vertical light pipes (usually without anidolic collectors) no commercial systems are around to choose from. And because of lack of planning tools and guidelines, architects and engineers refrain from considering these systems. The authors argue that using the traditional daylight factor approach also does not help in the proliferation of anidolic daylight collectors. It is rather a simple measure averaging the daylight performance of the whole system into one value,
without providing detailed design parameters to understand the causal relationship between the contour and performance of a collector. One could not differentiate a system with poor collector but excellent internal funnel (high internal reflection) from one with an excellent collector but weaker funnel performance. Both would probably yield the same daylight factor. However, the importance of the collector and thus knowhow for the design is obvious: a good collector can collect and collimate the light much better, so that much lesser reflections (and thus losses) occur inside the funnel, meaning light can be transported over longer distances. In other words, for a given distance, there will be the same brightness with much less reflective and thus less expensive surface material.

3. Structure of the paper

Section 4 introduces different reflector designs. The new performance criteria as a function of the LIDC are introduced in Section 5. The computational simulation to arrive at the LIDC is described in Section 6. Section 7 tabulates the performance results for all reflectors based on above techniques. Sections 8 and 9 include discussions and conclusions.

4. Examples of different collectors

The contours of the collector as seen in Fig. 2 comprise of compound parabolic concentrators (CPC) and de-concentrators. (Rabl, 1976a). They are complemented by two simple flat collectors serving as reference. While the contour varies, the height for the exit aperture abutting the horizontal funnel is fixed to 0.5 m. Their length (horizontal protrusion from the facade) varies between 0.5 m and 1.3 m. Type 1 collector is a parabolic concentrator with an entry aperture of 90° to collect any daylight between horizon and zenith. Type 2 is a combination of a scaled-down type one and an additional de-concentrator to collimate the light to around ±40° from the horizontal funnel axis. Type 3 is a variation of type 2 with a larger de-concentrator to narrow the spread even more. For both types, the concentrator was scaled down proportionally to fit into the stipulated height of 0.5 m. In types 4 and 5 upper de-concentrators were added basically as mirror copies of those

![Fig. 1. Section of office room with integrated anidolic elements (external collector and internal emitter) and connecting funnel (light duct). Source: Scartezzini et al.](image)
in types 2 and 3. Two simple flat baffle collectors with 45° (type 6) and 26.6° (type 7) complete the set of collectors. The shapes for all concentrators and de-concentrators are generated through a special software for a given acceptance angle, edge rays and overall height (kämpf, 2000).

5. Proposed performance criteria

LIDC are already established formats for illustrating the luminous intensity distribution of light sources. Intensities are charted over defined horizontal angles \( \varphi \) (called \( C \)-planes) and vertical angles \( \theta \) either absolutely or relatively per 1000 lumen luminous flux. The authors suggest adopting the LIDC standard for quantifying the luminous intensity distribution of anidolic collectors. The set new performances criteria can all be derived from a LDIC; either generated through forward ray tracing simulation techniques as in our case, or through actual measurements.

5.1. 2D flux

This is a general descriptor how much light is collected. Focusing on the collector’s two-dimensional geometry in the \( XZ \)-plane, the 2D flux \( \Phi_{2D} \) in a single vertical plane, which combines two opposite \( C \)-planes from the LIDC at horizontal angles \( \varphi_C \) and \( \varphi_C + 180° \) can be examined. Fig. 3 shows this light as shaded in grey in the LDIC for collector type 1 for example. The 2D flux can be calculated as:

\[
\Phi_{2D}(\varphi_C) = \int_{-\pi}^{\pi} \text{LIDC}(\varphi_C, \theta) d\theta
\]

where

\[
\text{LIDC}(\varphi_C, \theta) = \begin{cases} 
\text{LIDC}(\varphi_C, \theta) & \text{if } \theta \in [0, \pi], \\
\text{LIDC}(\varphi_C + \pi, -\theta) & \text{if } \theta \in [-\pi, 0]
\end{cases}
\]

5.2. Percentage of 2D flux for a given angular spread

This is a descriptor how much of the collected light leaves the collector within a given angular spread as illustrated in Fig. 4 for \( \pm 27.5° \). The ratio \( P \) within a certain angular spread \( \pm \delta \) around a defined angle \( \alpha \) in this \( C \)-plane (usually the \( C0-C180 \) or the \( C90-C270 \) plane) can be calculated as:

\[
P = \frac{\int_{-\alpha}^{\alpha+\delta} \text{LIDC}(\varphi_C, \theta) d\theta}{\Phi_{2D}(\varphi_C)}
\]
and use percentages $100P$ for displaying results. $\alpha$ is $0^\circ$ when the direction of light is along the horizontal funnel axis. The percentage can be derived for any spread $\delta$, e.g. $\pm 27.5^\circ$, an angle within which optical lighting films would reflected almost 100% of the light based on total internal reflection.

### 5.3. Horizontal offset and 90% field angle

Light leaving the collector can be perfectly symmetrical to the horizontal duct axis or point up- or down-wards. A horizontal offset is only desirable if a connected duct is also off the horizontal axis or when, in absence of a duct, light needs to be directed upwards to the ceiling for further diffusion into the room. A quantifier for the horizontal offset angle is needed and the angle of a centerline that divides the 2D flux into two equal parts is proposed as illustrated in Fig. 5. Based on the percentage of 2D flux the central line $CL$ of the 2D flux in the $C$-plane can be calculated by its angle $\alpha_{CL} \in [-\pi, \pi]$. 

$$\frac{\int_{-\pi}^{\pi} LIDC(\phi_C, 0) d\theta}{\Phi_{2D}(\phi_C)} = \frac{\int_{-\pi}^{\pi} LIDC(\phi_C, 0) d\theta}{\Phi_{2D}(\phi_C)} = 0.5$$  \hspace{1cm} (4)

$\alpha_{CL}$ is zero whenever a collector system redirects light perfectly along the axis of the duct. A positive or negative value indicates light is leaving the collector upwards or downwards, respectively. Additionally, the angular spread can be limited to $\delta_90$ where 90% of the 2D flux happens as illustrated in Fig. 6.

$$\frac{\int_{-\pi}^{\alpha_{CL}+\delta_{90}} LIDC(\phi_C, 0) d\theta}{\Phi_{2D}(\phi_C)} = 0.9$$  \hspace{1cm} (5)

### 5.4. Concentration ratio

A traditional measure to describe the performance of a concentrator is the concentration ratio $C$ which is defined as:

$$C = \frac{A}{A'}$$  \hspace{1cm} (6)

where $A$ is the area of the concentrator’s entrance aperture and $A'$ is the area of its exit aperture. In the two-dimensional approach this ratio can be expressed in terms of lengths instead of areas. Thus, $C$ is calculated as:

$$C = \frac{l}{h}$$  \hspace{1cm} (7)

where $l$ denotes the length of the concentrator and $h$ is the height of the exit aperture.

### 6. Computational simulation techniques

Ray tracing based simulation has been shown to be a valuable aid to predict the performance of daylighting systems. Back-ward ray tracers such as RADIANCE are known to be inefficient with many specular reflected indirect light rays as in the case of a daylight collector with attached funnels.

For the purpose of this paper the commercially available forward ray tracing software package PHOTOPIA (LTI, 2008) in its current version 3.0, has been selected. It is a 3D CAD based simulation software frequently used by designer of optical system including reflectors and lenses and includes a large library of commercially available lamps and materials. It calculates and exports LIDCs and was validated for the performance assessment of tubular light pipes (Dutton and Li, 2007). The set-up as described below is generic and can be modeled in other suitable software such as OPTICAD and Photomap (PMAP) as well. For use in such 3D simulation software the 2D contours of the collectors were extruded by 1.50 m along the $Y$-axis as shown in Fig. 9 for collector type 4. Alternatively, a 2D study could have been conducted, but this 3D simulation allows the future analysis of 3D geometries that cannot be adequately represented by 2D contours.

#### 6.1. Arc-shaped light source

To allow the efficient 2D assessment of a 3D model, a light source was set-up that shines ideally in the plane containing
the collector axis and the vertical as illustrated in Fig. 7. The light source is thus a narrow vertical slice of the sky vault, forming an arc located in front of the collector entry. The arc light is divided into eight planar segments following international standards for the subdivision of the sky hemisphere (Tregenza, 1987). Each segment is defined as a light source with constant intensity within ±6° beam and linearly fading out until ±12°. Their overlapping light beams create diffuse illumination around the center of the arc, where the collector entries will eventually be positioned. Following requirements for far-field photometry, the radius of the light arc was set to 10 m compared to the size of the luminaries, where one arc segment is 2.1 m high and 3.6 m wide. This also ensures that every point on the 1.50 m wide collector receives light from all angles. The authors use a luminous flux of 22,817 lumen for each segment to reach an average illuminance of 10,000 lux at the horizontal reference plane located at the collectors’ entrances. Fig. 8 shows a horizontal illuminance plane covering all collectors’ entry apertures. The bottom horizontal lines denote the photometric center from where the collectors opening extend upwards. The horizontal lines denote the position of the edges of the entry apertures for all seven collectors. Systems with de-concentrators are longer (horizontally) than those without, while those with baffles are the shortest. As the position of photometric center of the LIDC has to be same for all collectors.
These varying lengths result in slightly different locations of the aperture entries. Long systems, such as type 2 have an entry opening slightly closer to the lower elevation light source. However, the average illuminance across all collectors varies only around 3% and this variation can thus be neglected.

While the initial set-up uses a uniform distribution, the flux of the light sources could be controlled individually, so that various standard sky luminance distributions (ISO, 1546) could be represented. One modified set-up, consisting only of the segments at 66°, 78° and 90° is used with two collectors, types 1 and 5, to assess the performance for zenith light only.

### 6.2. Measurement planes

The photometric measurement of the collector takes place at the center of the exit apertures. As the distance between the light source and collector entry is kept constant across all collectors’ simulations, the varying internal distances between collector entry and exit, leads to slight variations of distances of photometric measurement center and light source. However, these horizontal differences matter only from the lower light segments and become insignificant for the upper light segments. Fig. 9 shows collector type 4 with the 0.5 m wide horizontal reference illuminance plane above the collector entrance and the 0.5 m × 0.5 m vertical test illuminance plane at the exit of the collector. Further vertical measurement planes (0.5 m wide and 0.5 m high) are located at 5 h (or 5 × 0.5 m = 2.5 m) intervals from the exit aperture inside the funnel to quantify the light attenuation. No openings for extractors are included in the funnel to relate the light fall off only to the collector contour without any interference with light fall off due to sequential extraction. Basic equations for light fall offs caused by these emitters or extractors are given for hollow light guides (Edmonds et al., 1997).

### 7. Results

Fig. 10 illustrated the paths of light rays through the whole system as simulated by Photopia. Rays originate from the arc light source (right) and converge in the center of the light arc creating the desired diffuse daylight at the collector entry aperture. Rays received by the collector are directed into the horizontal funnel passing through the various vertical measurement planes to eventually leave the system at the funnel exit on the left. The funnel end was kept open to exclude interfering reflections from the back end.

A detailed close up of rays intersecting with selected collectors is shown in Fig. 11. The images in the left column show how rays incident at 60° intersect with the anidolic and baffle collector. Note that the baffle collector partially rejects rays, while the anidolic concentrators accept all. The collimating effect of the additional de-concentrators becomes evident as well. The images in the right column...
superimpose rays from various incident angles, showing the typical converging point at the collector edge for rays admitted at 90° and the shifting of the convergence zone to the left with lower incidence angles.

Eventually, Fig. 12 shows the C0–C180 planes of the LIDCs for the seven collector systems where the collectors’ outlines were added on the right hand side of the scale for illustrative purposes. With a parabolic shape of type 1 light leaves the collector almost perfectly diffuse spreading over nearly the full left hemisphere (C0–180-plane), basically keeping the diffuse spread of light in front of the collector. Adding a de-concentrator (type 2) however shows at better collimation at the expense of overall intensity, a trend that becomes stronger with a larger de-concentrator in type 3 due to the smaller parabolic collector (to keep to the 0.5 m height limit). Adding further de-concentrators improve the symmetry of the spread. Collectors 6 and 7 (flat baffles at 45° and 26.6°) show the most asymmetrical spread over the funnel axis, with most light redirected in a downwards manner and a clear cut off of the upward spread. This is because most of the downwards shining light rays will reach the collector exit without intersecting with the collectors. All LIDCs show similar range for the maximum ranging between 8000–9000 candela.

With the presence of the LDIC the above performance criteria can be calculated to allow for more informed comparison. They are tabulated for all seven collectors in table 1.

8. Discussions

8.1. 2D flux

The plain parabolic collector type 1 performs best in terms of 2D flux (16,730 lm), followed by the straight baffle type 7. This is not surprising as both types have the largest collector opening. The flux at the exit of the type 1 collector is about 3000 lumen higher than the flux of the straight baffle collector, simply because the parabolic shape collects light more efficiently with the same opening surface because of its wider acceptance angle. Adding de-concentrators to the parabolic shape reduces the flux by more than 5000 lm due to the reduced sized of the collector openings up to the extreme case where due to the two relatively large de-concentrators in type 5 the size becomes only half of type 1. So, if maximum flux at the collector exit was the design objective, a parabolic collector of type 1 would be the ideal choice. Actually, in practice straight baffle type 7 would be preferred for ease of construction. If that would still be the best choice if transportation over long funnels were to be considered remains a problem to be looked at with the following criteria.

8.2. Percentage of flux within ±27.5°

The ranking is inverted when looking at the flux within a specified narrow angle as charted in Fig. 13. Setting the
angle to 55° (or ±27.5° producing total internal reflections without significant losses using optical light film) would make the former best performer parabolic type 1 now the worst performer as less than 50% of all emitted light falls within this range. In contrast, type 5 shows the highest yield with close to 90%. Straight baffles such as types 6 and 7 show around 50% yield. Hence, adding the collimation as design criteria would result in an opposite choice.

Fig. 12. C0–C180 planes of LIDCs for the seven collector systems with collector’s outlines attached.
However, with percentages of 71% for types 3 and 4 and 87% for type 5 in the 55° field, these collectors partially compensate the lower flux by redirecting more light into the directions close to the funnel axis. From the 2D flux and the 55° field percentages, absolute values for the partial 2D flux within the angular spread of ±27.5° can easily be calculated by multiplying them. Values of 7479, 6867, 7256, 7223, 6858, 4085 and 7498 can be obtained for collector systems types 1–7. Considering this measure, type 7 performs best followed by type 1, but the values are quite similar for all collector systems except the 45° flat baffle of type 6, which performs worst.

### 8.3. Central line and 90% field angle

The angles $z_{CL}$ for the central lines of the 2D fluxes of the seven collector systems show varying horizontal offset angles. The angular spread $\pm \delta_90$ around $z_{CL}$, which is necessary to cover 90% of the 2D flux also varies significantly. As already indicated by the LIDCs in Fig. 12, the systems with the de-concentrators e.g. types 4 and 5 collimate the light the best, with type four having the desired narrower spread.

The impact of this is illustrated in Fig. 14, as light fall off in an abutting funnel in terms of illuminance ratios relating to the illuminance at the particular collector exit, i.e., the beginning of the funnel. Regarding this ratio, type 5 performs best as it shows the lowest attenuation, followed by types 4 and 3. From this figure one can also derive the normalized distance from the collector exit where 50% of the light flux is absorbed. These ‘cut-offs’ happen at 11 h for types 1 and 6, 14 h for type 7, 16 h for type 2, 21 h for type 3 and 4, and 28 h for type 5. For an actual funnel of $h = 0.5$ m, the cut off with type 5 would be at 14 m.

### 8.4. Concentration ratio

The direct correlation between the concentration ratio and previous criteria is evident. The lowest ratio of 1 for a collector system where height equals collector entry length, as almost given for type 5, yields the lowest angular spread, or best collimation. However, there is no such correlation for the straight baffle collectors.

### 8.5. Non uniform daylight

The current results present a case with daylight of uniform distribution pattern falling onto the collector opening. The generic set-up in the computational simulation allows the modeling of a non uniform light distribution from horizon to zenith as well. In Singapore, for instance, located on the equator where the sun travels overhead, the
zenithal portion of the sky is much brighter than the horizon. For this case, the lower lights (segments of the arc light source) can be dimmed down or switched off to also consider over shading from surrounding buildings.

Two collectors, types 1 and 5, were chosen to compare their performance considering only light coming from high elevation angles under 66–90°. The choice was based on the previous results, which had identified type 1 as guiding the highest luminous flux into the funnel, while type 5 had shown the highest performance in shaping the exiting beam into a desired exit angle of 55°. As the whole arc light is still completely within by the acceptance angle, the luminous flux collected remains unchanged and still only depends on the illuminance, which has been set to the same 10,000 lux as in the case of uniform daylight. Fig. 15 shows the LIDC’s for types 1 and 5 for both uniform and zenithal daylight. The exit distribution of type 1 depends on the directions under which incoming illuminance is received by the collector, the spread leaving type 5 is only defined by the geometry of its de-concentrators, leading to exactly the same exitance distribution for any incoming direction as long as the illuminance at the entry and thus the luminous flux received remains constant and the sources are within the acceptance angle.

The different exit distributions are illustrated for horizontal and vertical illuminance ratios for types 1 and 5 collectors illuminated with zenith light (66-90°) in Fig. 16. Type 1, guiding more light into the funnel due to its diameter, exhibits high illuminances on the horizontal measurement plane, while type 5 directs the flux almost parallel to the duct axis, resulting in lower horizontal illuminances. However, type 5, due to very little losses at the reflector surfaces, shows an almost constant illuminance on the different vertical measurement planes. Thus while type 1 certainly would perform well on the first meters, type 5 allows guiding light further through the light duct. The effect of the fewer reflective bounces and thus little reflective losses of type 5 would become even more significant when reflective duct surfaces with a lower reflectance grade or lower specularity would be used, and thus suffer less from aging effects, contaminations or surface imperfections.

9. Conclusion

A novel method for quantifying the performance of anidolic daylight collectors is presented that goes beyond the currently used daylight factor approach, focusing on the collector and providing descriptors for its detailed assessment and thus optimization. New criteria such as 2D flux, percentage of 2D flux within a selected angle, horizontal offset angle and angular spread were proposed to quantify the optical performance of anidolic daylight collectors, based on luminous intensity distribution curves (LIDC). A method to derive LIDC with forward ray tracing simulation techniques was introduced together with equations indicating how the quantities of the performance criteria were calculated as a function of the LIDC. This method was applied to compare various collector designs which brought about the pros and cons of various collector types.

Transportation of daylight over longer distances requires an optimized collector using de-concentrators, however at the expense of a larger funnel to collector entry size ratio. If this larger space for the funnel is available, high collimation and thus low light attenuation can be achieved. In addition, the extractor and emitters such as laser cut panels, eventually redirecting this light into spaces below, can be much more effective if they receive collimated rather than diffuse light (Edmonds et al., 1997; Kwok, 2008). Systems with simple baffle and parabolic reflectors can capture more light, just because their entry opening is larger, however they keep the diffuse character of the incident light so that light leaving it has a wide spread. This can be desired in the absence of a funnel or when funnels can be kept rather short.

An optimized collector ensures best light capturing and is most cost effective when reducing losses by limiting the number of reflection bounces instead of expensive
countermeasures such as extremely high reflectance grades. On the other hand, some reflective materials such as optical light films would require a certain range of oblique light rays in order to provide total internal reflection. A similar precise direction would be required when using laser cut panels as extractors, so that well defined portions of the horizontal light flow can be directed vertically through exit apertures for room illumination. The presented methodology and derived performance criteria helps to optimize these applications.

10. Future work

The proposed methodology provides a base for further work, which could focus on the development of new collector contours supported by these performance criteria. Variation of acceptance angles, including their interplay with various reflecting materials can be analyzed as well as the impact of truncation of large collectors which has been found an effective way of reducing the collector size without much performance losses. The current sky conditions of uniform luminance distribution between horizon and zenith can be adjusted to represent the various CIE/ISO skies or actual measured sky luminance. For non uniform light distributions the collector designs can be further optimized by narrowing the acceptance angle and aligning them to the brightest parts of the sky. In view of the lighting conditions in cities in the tropics such as Singapore with mainly high-rise buildings, collectors would thus be optimized to capture light mainly from the zenithal parts of the sky. Finally, after the collectors, funnels and diffusers have been constructed as part of the zero-energy building in Singapore; actual measurements can be taken and compared with the computational simulations.

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