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Design of an anidolic concentrator and evaluation of daylight enhancement under an overcast sky

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This paper discusses the performance evaluation of anidolic concentrators in an overcast sky condition. The concentrators were designed, with acceptance angles of 60°, 70° and 80°, first by maintaining the profile of the concentrator's uniform and secondly by keeping the height uniform. Studies were done using these concentrators with a model light pipe and the performance was compared with that of an acrylic dome and a profiled Fresnel collector. For a given condition, the illuminance ratio (ratio of illuminance measured at the base of the pipe to external illumination) increased with the acceptance angle. For a given acceptance angle, the concentrator with uniform height and variation of entrance aperture, performed better than a concentrator having a uniform profile.

1. Introduction

Traditional passive collectors in light pipes, due to their static nature, do not consider the variation of the sun's altitude, azimuth and declination. Passive and profiled north facing and south facing collectors[1] with a multi-surface Fresnel lens system were designed in a recent study by the authors based on the solar altitude and azimuth angle of a particular geographical location. The design objective was to orient Fresnel surfaces perpendicular to the position of the sun at different periods of the day. Each of the surfaces focuses sunlight at varying intensities at multiple points in a light pipe unlike an acrylic dome, which focuses at one point in a light pipe at any given time. These multiple focal points help in achieving more uniform light output through the light pipe. Laser cut panels were integrated with the profiled Fresnel lens collector, which facilitated redirection of daylight axially into the light pipe to increase the light transmission during morning and evening hours.[2]

As the sky clearness index decreases under diffuse and overcast sky conditions, the amount of inter-reflections within a light pipe with a conventional acrylic dome collector increases, resulting in lower light transmission.[3] The Fresnel collector had the limitation of low light transmission under an overcast sky as the Fresnel lens works on the imaging optics principle.[2] Hence, there is a need for identifying an efficient system to capture daylight into buildings under overcast sky conditions. This observation necessitates the adoption of non-imaging optics.

Anidolic or non-imaging systems have been utilised to redirect diffuse light from the sky

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to interiors and they are suitable in areas where overcast sky conditions are common.[4] Non-imaging optics is the study of optical systems that maximises the efficiency of light transmission, concentration and deconcentration without producing images[5] and was originally developed for solar concentration.[6–9] Use of non-imaging optics avoids the need to keep the concentrator aperture pointed at the sun.[9] Solar radiation is concentrated either by concentrators like a cone[10] or a V-trough,[11] but the efficiencies of these concentrators are low under an overcast sky.[12] Compound parabolic collectors have higher efficiencies and can be utilised in such situations.[11]

Under overcast sky conditions, daylighting enhancement in buildings is provided by non-imaging systems like an anidolic ceiling, an integrated anidolic ceiling and anidolic solar blinds.[13] These systems have a range of predefined acceptance angles and hence much of the sky and ground reflected illumination is rejected. But when used in tropical climates with clear skies, excess heat and glare is produced inside the building.[5] Moreover, these systems have large collection areas and hence are space intrusive.[13] Anidolic zenithal light guides[14] and anidolic concentrators, being top-lit, are ideal in overcast skies as the luminance of the zenith region of an overcast sky is higher than that received at the horizon.[15] They are more compact than other non-imaging devices (anidolic ceiling, integrated anidolic ceiling) and can be integrated with a light pipe. Through analytical and simulation studies, Taengchum and Chirarattananon[16] concluded that (i) the addition of an anidolic concentrator at the entry port of light pipe increased daylight capture and (ii) it reduced the overall cost per unit of delivered daylight luminous flux, especially for long pipes and pipes with bends. Simone *et al.*[14] studied anidolic concentrators connected to a roof-mounted pipe under a sky scanning simulator and observed that the performance of the pipe increased quantitatively and qualitatively. The efficiencies of the anidolic ceiling, the integrated anidolic ceiling and the anidolic zenithal opening are reported to be 32 %[13], 19–26 %[13] and 36 %[5], respectively.

An anidolic concentrator is a compound parabolic concentrator[17] (CPC) comprising two meeting parabolas. It is built with highly reflective material and the concentration is achieved by its parabolic form (a two-dimensional (2D) CPC with flat mirrors or a three-dimensional (3D) CPC made through the rotation of a 2D profile around its symmetry axis); with diffuse light falling on the entry aperture of the device collected and concentrated into a smaller exit aperture.[7] In an anidolic concentrator, (i) light with an incidence angle less than half the acceptance angle is reported to be reflected through the exit aperture and (ii) light with an incidence angle greater than one-half the acceptance angle will be rejected back[7] (Figure 1(a)). As seen in Figure 1(b), the entry aperture has a lower angular range, whereas the concentrated light could be emitted out at a wider angular range.

It has been reported that these concentrators act as radiation funnels having no focus. They have also been designated as some of the concentrators that have the highest possible concentration permissible by the thermodynamic limit for a given acceptance angle.[9,12] Due to their large aperture areas and acceptance angles, only intermittent tracking may be required[12] and they have potential for collection of thermal energy.[18]

The amount of diffuse radiation collected by a concentrating collector is given by $1/C$, where C is the concentration ratio. Concentration ratio is also defined by the ratio of entry aperture area to exit aperture area.[8] The general concentration ratio achieved by a CPC is reported to be in the range of 3–10, whereas that for a cylindrical parabolic collector and parabolic dish collector it is more than 1000 where it is used in solar thermal power systems.

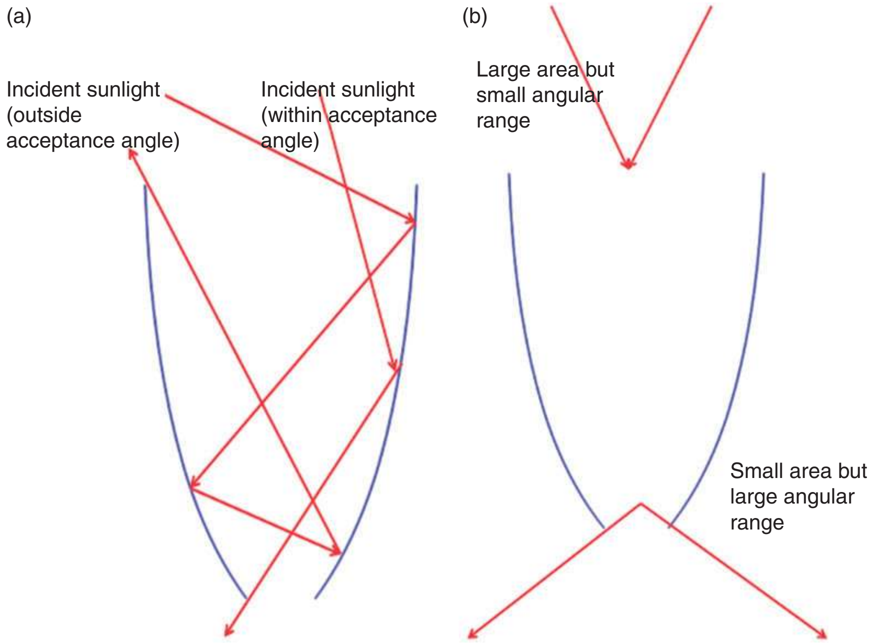

Figure 1 An anidolic concentrator. (a) Concentrates light within its half acceptance angle. (b) Input aperture has larger area but smaller angular range.[7]

In practice, higher acceptance angles are suitable for collecting diffuse radiation and solar light over a wider range of time at the expense of a lower concentration ratio.[8] It was observed that lower (less than 3) concentration ratio CPCs are of greatest practical interest as a higher concentration ratio necessitates higher manufacturing precision.[17] A major advantage of this concentrator over the other collectors is that the ability to collect diffuse radiation makes it suitable for overcast sky conditions.[19] Further, these concentrators are able to accept a large proportion of diffuse radiation incident on their apertures and concentrate it without the need for tracking the sun.[20]

Based on the above mentioned review, the anidolic concentrator offers itself as a potential collector for directing light through a light pipe under overcast skies. The present study focuses on the influence of acceptance angle of the anidolic concentrator on its performance.

2. Methodology

The anidolic concentrator is a passive collector, which has to suit the solar movement of the geographical location proposed. For the study location, the city of Chennai (13°4′N, 80°15′E, GMT +5.5 hours) was chosen and the solar altitude angle throughout the year was considered for the design. The following parameters were considered for the design of the concentrators:

(i) Acceptance angle: Anidolic concentrators of acceptance angles varying between 60° to 80° were designed and fabricated as a higher acceptance angle is suited for transmitting both direct and diffuse solar light.[8] For acceptance angles of 60°, 70° and 80°, the solar altitude angles need to be higher than 60°, 55° and 50°, respectively. A concentrator having higher acceptance angle can capture sunlight for a longer duration in a day.

(ii) Configuration: The above acceptance angles can be achieved by the following two methods and the detailed design has been outlined in the next section.

   (a) Maintaining a uniform profile of the concentrator (constant profile method).
   (b) Maintaining a uniform height of the concentrator (constant height method).

3. Construction of anidolic concentrators

3.1. Maintaining a uniform profile of the concentrator

Keeping the shape/profile constant and having variations in height could result in the chosen range of acceptance angles, but the entry and aperture dimensions also get varied. The height, entry aperture and the concentration ratio have been derived from equations (1) to (3) of Rabl[7] and are reproduced below.

$$\text{The overall height (H) is } \frac{\alpha'(1+\sin\theta_i)\cos\theta_i}{\sin^2\theta_i} \quad (1)$$

$$\text{The diameter } (2\alpha) \text{ of the entry aperture is } \frac{2\alpha'}{\sin\theta_i} \quad (2)$$

The maximum possible concentration ratio (C) for a given half acceptance angle

$$\theta_i, \text{ is } C = \frac{1}{\sin^2\theta_i} \quad (3)$$

where θ_i is the maximum input angle or half acceptance angle and $2\alpha'$ is the exit aperture diameter. By reducing the acceptance angle the height and diameter are increased and vice versa. It should be noted that a low acceptance angle results in increased bulk of the concentrator and hence greater material cost.

The configuration of the anidolic concentrator having an acceptance angle of 60° is shown in Figure 2 where the shape of the CPC is determined in terms of the diameter of the exit aperture ($2\alpha'$) and the maximum input angle or half acceptance angle (θ_i). It has two parabolic sections BD and AC of parabola 1 and 2, respectively. AB is the entry aperture, whereas CD is the exit aperture. The axes of both parabolae are oriented such that C is the focus of parabola 1 and D is the focus of parabola 2. The height of the concentrator (H) is such that tangents at C and D are parallel to the axis. In Figure 2 it can be seen that the incident rays are the extreme rays of the beam, so the height of the concentrator must be such that they pass the rays.[7] Figure 3 illustrates concentrators of varying acceptance angles (60°, 70° and 80°) with a uniform profile and having an exit aperture width of 150 mm. The height dimensions (xa, xb and xc) and the entry aperture dimensions (AA′, BB′, CC′) seen in the Figure 3 are presented in Table 1.

Three anidolic concentrators were designed by keeping the height and exit aperture constant, but varying the profile such that the acceptance angle and the entry aperture varied. The radii (α) of the entry aperture of the concentrators of varying acceptance angles were obtained by using the relationship which was derived from the construction method proposed by Rabl.[7] This relationship is

$$\alpha = \mathrm{H}\tan\theta_i - \alpha' \quad (4)$$

The profile of the concentrators was designed such that O_1 is the focus of the parabolae AO, BO and CO. Similarly, O is the focus of the parabolae A_1O_1, B_1O_1 and C_1O_1, respectively. Figure 4 illustrates the three concentrators having their profiles varying with the exit aperture of 150 mm. Table 2 presents the entry aperture sizes of

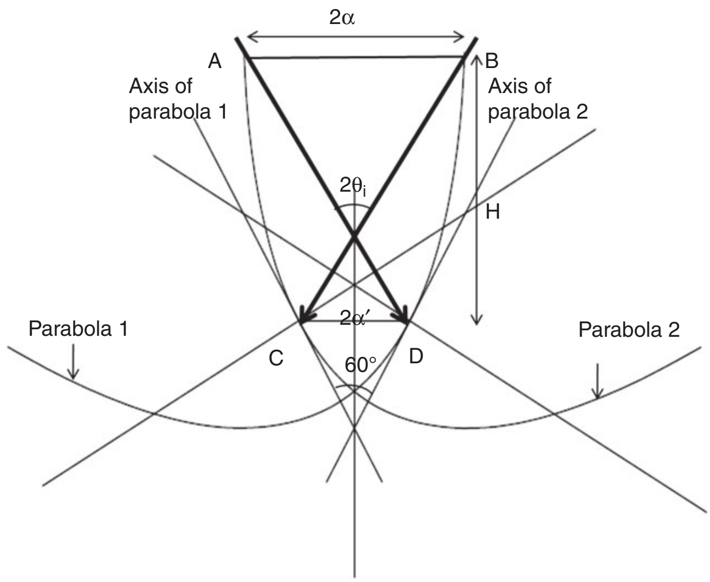

Figure 2 Construction of parabolae for an anidolic concentrator

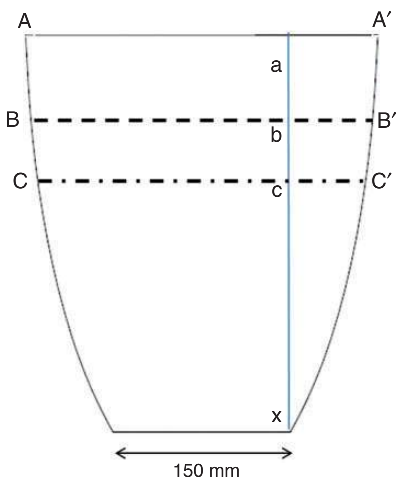

Figure 3 An anidolic concentrator with uniform profile but varying height

CPCs with exit aperture width 150 mm and 200 mm with a uniform height of 390 mm but with varying acceptance angles. The corresponding values for the entrance aperture (AA_1, BB_1, CC_1) for the exit aperture of 150 mm are presented in Table 2.

The concentrators were fabricated of 1.2 mm thick polished stainless steel sheet. A computer numerical control (CNC) machine was used for cutting the profile of the concentrator. The cut profiles were bent according to the profile and welded together. Experiments were done with a model light pipe of aspect ratio 2 (length 600 mm and diameter 300 mm) having aluminium sheet as internal reflective material (0.52 reflectance). The pipe was mounted on a box of size 400 mm × 400 mm × 100 mm.

Figure 5 represents two model light pipes with an anidolic concentrator and acrylic dome both having entrance apertures of the same size (300 mm). The illuminance (E_{int}) was measured at the centre of the base of the box along with simultaneous measurement of external illuminance (E_{ext}). The illuminance ratio (E_{int}/E_{ext}) was thus calculated. Light output was measured using a Extech (HD 450) data logging lux meter having a range of 0–400 klx. The performance of the designed concentrators was assessed on a typical day under an overcast sky condition and then under a clear sky condition in Chennai.

Table 1 Specification details of anidolic concentrator with uniform profile

Acceptance angle ($2\theta_i$) (degrees)	Concentration ratio	Exit aperture (150 mm)		Exit aperture (200 mm)	
		Entry aperture (mm)	Height (mm)	Entry aperture (mm)	Height (mm)
20	33	860	2880	1150	3830
30	15	580	1360	770	1820
40	9	440	810	590	1080
50	6	360	540	470	720
60	4	300 – AA′	390 – xa	400	520
70	3	260 – BB′	290 – xb	350	390
80	2	230 – CC′	230 – xc	310	300

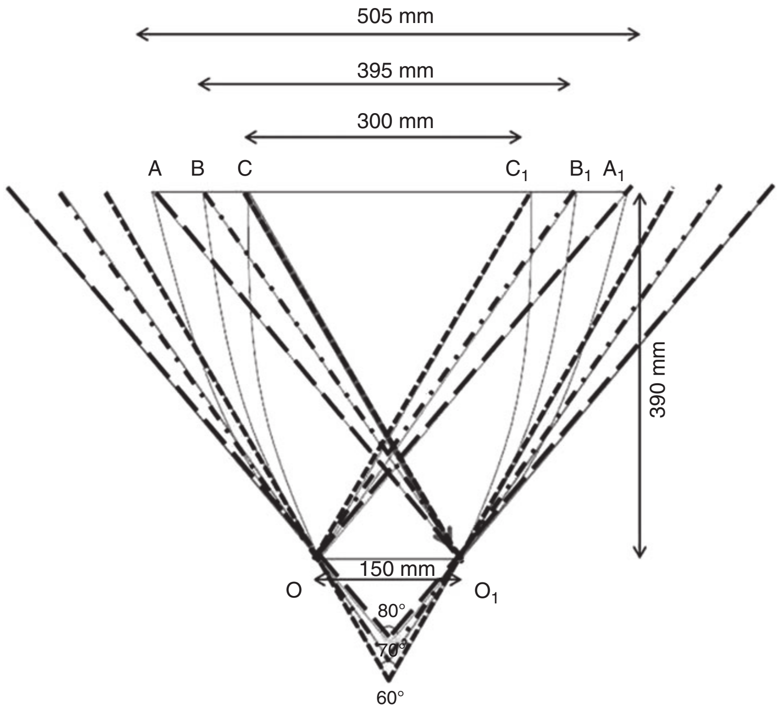

Figure 4 Anidolic concentrators with uniform height but varying entry aperture size

4. Performance

4.1. Constant profile with varying height (AC-1)

The performance of the concentrators with varying height resulting in three acceptance angles (60°, 70° and 80°) was assessed in January on a cloudy day (the solar illuminance ranged from 7 Klux to 38 Klux) and the results are presented in Figure 6. The sky was overcast, with steep luminance gradation and slight brightening towards the sun which can be classified as a CIE overcast type 2 (gradation I) sky.[21]

The concentrator with an acceptance angle of 70° (i.e. with half acceptance angle of 35°) transmitted and concentrated light beyond a solar altitude angle of 55°. At 12.00 hours (solar altitude angle of 58°) a maximum illuminance ratio of around 0.51 was achieved, which decreased steeply with a reduction in solar altitude. In the case of the concentrator with the 80° acceptance angle, for a half acceptance angle of 40°, the concentrator could effectively accept light beyond 50°. It was observed that there was an increase of light output between 10.00 to 14.00 hours, where the solar altitude angle was approximately equal and exceeding 50°. When compared to the concentrator with an acceptance angle 70° it had a lower but more uniform light output between 10.00 to 14.00 hours, achieving a maximum illuminance ratio of 0.4.

Table 2 Specification details of anidolic concentrators with uniform height

Acceptance angle ($2\theta_i$) (degrees)	Exit aperture (150 mm)	Exit aperture (200 mm)
	Entry aperture (mm)	Entry aperture (mm)
30	59	9
40	134	84
50	214	164
60	300 – CC_1	250
70	395 – BB_1	346
80	505 – AA_1	454

4.2. Constant height with varying profile (AC-2)

Performance of the concentrators with varying profile was assessed under overcast sky condition (Figure 7) on a day with the solar illuminance ranging from a minimum of 15 Klux to 33 Klux in January. The performance of the concentrator increased significantly with an increase in acceptance angle. A maximum illuminance ratio of 0.73 could be achieved with the anidolic concentrator having an acceptance angle of 80°. Appreciable enhancement in illuminance ratio was achieved between 10.00 to 14.00 hours with this concentrator, where the acceptance angle was approximately equal to and exceeding 50°.

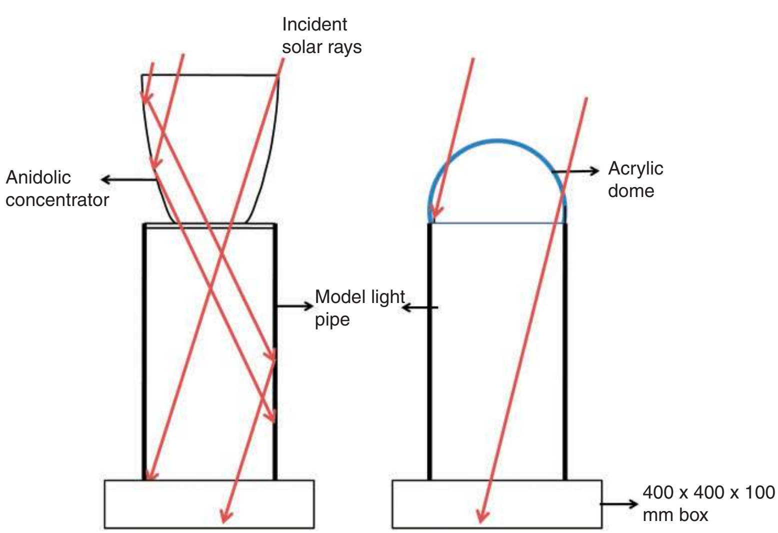

Figure 5 Illustration of a light pipe with an anidolic concentrator and an acrylic dome

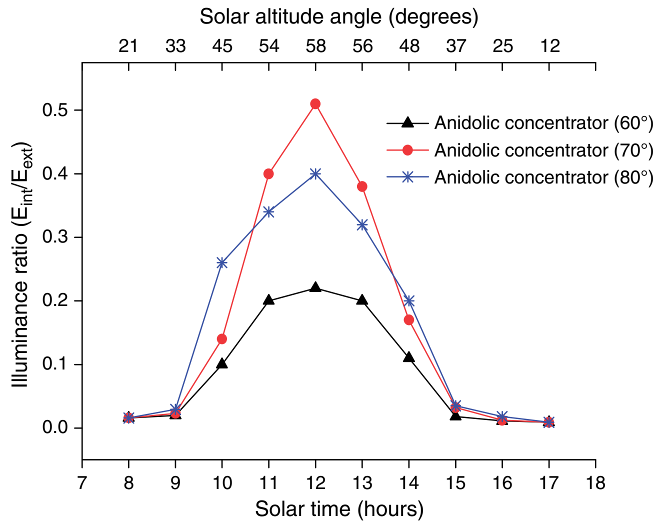

Figure 6 Performance of anidolic concentrators (uniform profile) under an overcast sky

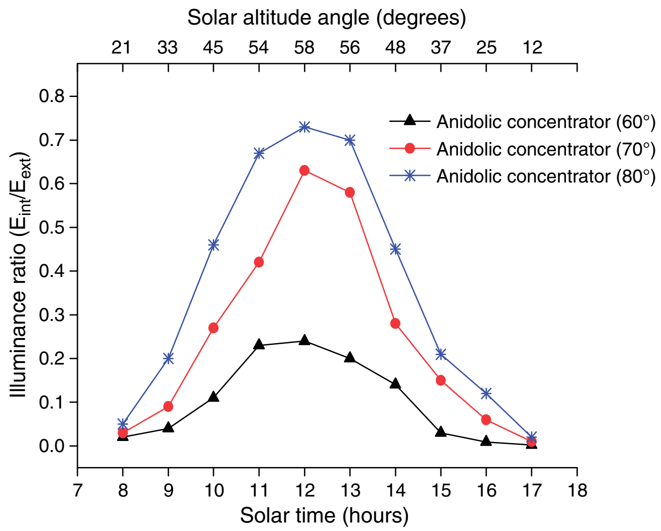

Figure 7 Performance of anidolic concentrators (uniform height) under an overcast sky

4.3. Concentrators of same acceptance angle constructed by the two methods

Anidolic concentrator 1 (AC-1: constant profile method) and anidolic concentrator 2 (AC-2: constant height method) having the same acceptance angle (70° and 80°) were compared along with the profiled south Fresnel collector integrated with laser-cut panel and an acrylic dome as shown in Figures 8 and 9, respectively.

It was observed that the anidolic concentrator having higher entrance aperture size

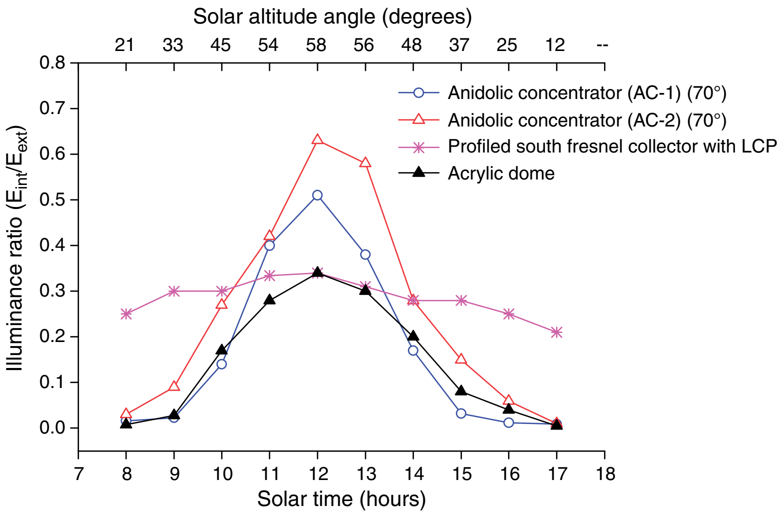

Figure 8 Performance comparison of anidolic concentrators (acceptance angle 70°) with other collectors

performed better than the one having the same acceptance angle, but lower entrance aperture size (Figure 8) between 10.00 and 14.00 hours. There was approximately a 120% increase in illuminance ratio at 12.00 hours for AC-2 compared with AC-1. Beyond this period, the illuminance ratio achieved through the anidolic concentrator was lower than that obtained through the south Fresnel collector.

Based on Figure 9, the following observations are made (i) illuminance ratio for the acrylic dome attained a maximum of 0.3 and decreased rapidly before and after noon; (ii) the profiled Fresnel collector integrated with LCP provides uniform low-light output throughout the day even in an overcast sky condition; (iii) the anidolic concentrator provided relatively higher illuminance ratio between 09.00 hours and 15.00 hours as compared to that of the profiled south Fresnel collector. Between the two types of anidolic concentrators, AC-2 produced a significantly higher illuminance ratio. There was an approximately 180% increase in illuminance ratio at 12.00 hours for AC-2 compared with AC-1.

Even though anidolic concentrators have been designed as collectors for use under cloudy sky conditions, their performance under clear sky conditions was evaluated and compared in the next section.

5. Performance of anidolic concentrators under a clear sky

The effect of solar altitude on the light output of the anidolic concentrator (acceptance angle 60°) having an entry aperture of 300 mm and height 390 mm was assessed at various times of the day (9.00 to 16.00 hours) in the month of April under a clear sky condition. The solar altitude angle varied from 47° at 9.00 hours and reached a peak of 87° at 12.00 hours. The light output was measured at the base of the concentrator at the exit aperture. It was observed that below 60° solar altitude angle, the incident light was reflected back without exiting through the output aperture.

As the solar altitude angle increased, the performance of the concentrator also increased. It was observed that the concentrator performed well between 10.00 (solar

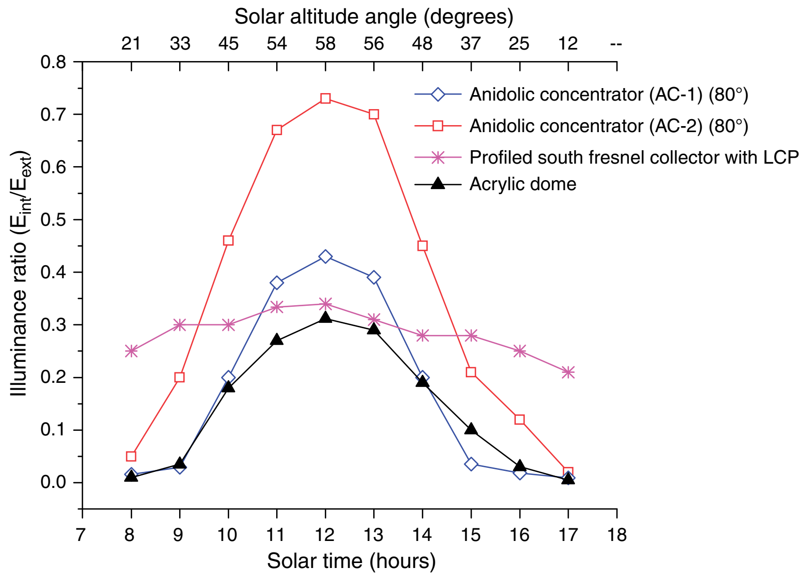

Figure 9 Performance comparison of anidolic concentrators (acceptance angle 80°) with other collectors

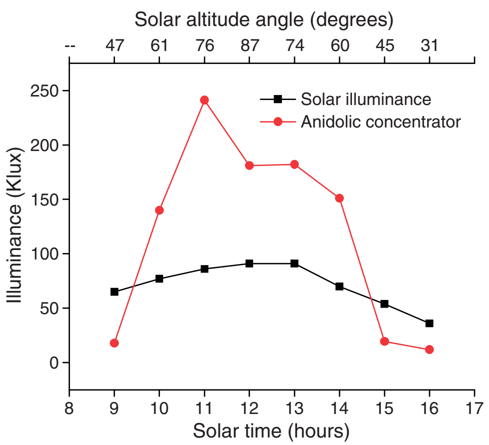

Figure 10 Performance of an anidolic concentrator under a clear sky

altitude angle 61°) and 14.00 hours (solar altitude angle 60°) (Figure 10). At 12.00 hours (solar altitude angle 87°) the incident solar rays exited through the exit aperture without any concentration.

5.1. Comparison of anidolic concentrators

The performance of the model light pipe with anidolic concentrators (AC-1 and AC-2) was assessed in the month of January under clear sky, when the solar altitude angle was low even at mid-day. The results are presented in Figures 11 and 12, which depict a behaviour similar to that observed under overcast sky condition with (i) higher illuminance ratio (0.74 under clear sky as against 0.51 for overcast sky in the case of AC-1; 1.05 as against 0.73 for AC-2), and (ii) the concentrator with higher acceptance angle had a greater light output due to the increased capture area.

6. Conclusion

The following conclusions are drawn from the present study, which are applicable to the parameters and their ranges considered in the study:

- For a given condition, the illuminance ratio achieved increased with an increase in acceptance angle.

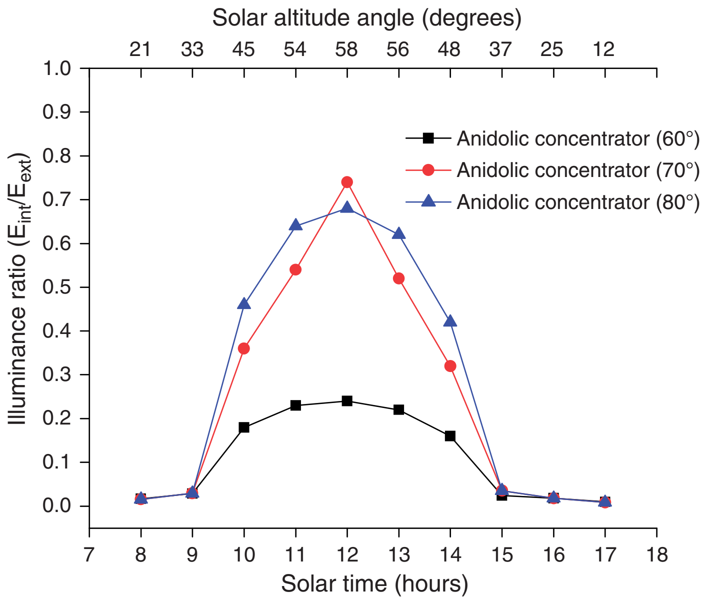

Figure 11 Performance of anidolic concentrators (uniform profile) under a clear sky

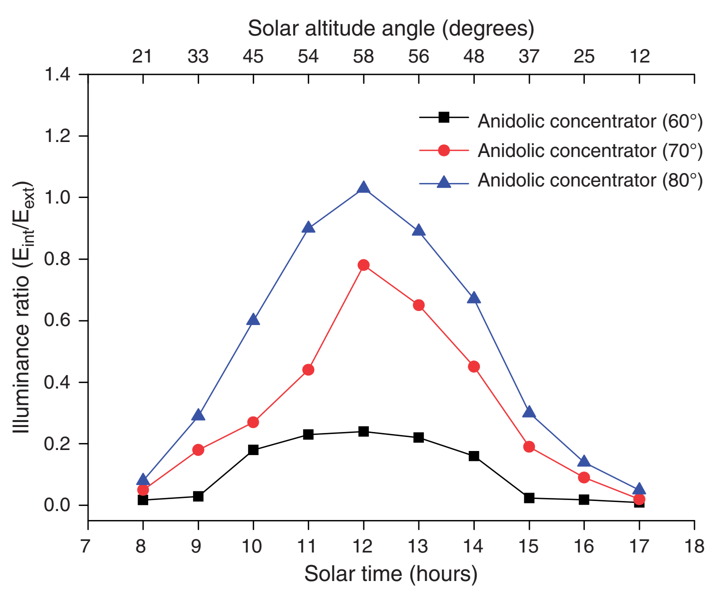

Figure 12 Performance of anidolic concentrators (uniform height) under a clear sky

- For a given acceptance angle, a concentrator with uniform height and variation of entrance aperture performed better than a concentrator having a uniform profile.
- There was nearly 120 to 180 % increase in the illuminance ratio at noon for the concentrators having 70° and 80° acceptance angles.
- Though the profiled Fresnel collector provided a uniform illuminance ratio throughout a typical overcast day, this ratio was low.

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References

1 Nair MG, Ramamurthy K, Ganesan AR. Conceptual design and assessment of profiled Fresnel lens daylight collector. *Lighting Research and Technology* 2014; 0: 1–15. First published 16 June 2014. doi: 1477153514535421.

2 Nair MG, Ramamurthy K, Ganesan AR. Day light enhancement using laser cut panels integrated with a profiled Fresnel collector. *Lighting Research and Technology* 2014; 0: 1–12. First published October 22, 2014. doi: 1477153514556524.

3 Zhang X, Muneer T. A mathematical model for the performance of light-pipes. *Lighting Research and Technology* 2000; 32: 141–146.

4 Johnsen K, Watkins R. *Daylight in buildings – a source book on daylighting systems and components*. [ECBCS Annex 29/SHC Task 21-Project summary report, July]. United Kingdom: AECOM Ltd, 2000.

5 Compagnon R, Scartezzini JL, Paule B. *Application of non-imaging optics to the development of new daylighting systems*: *Proceedings of ISES Solar World Congress,* Budapest, Hungary, 23–27 August 1993.

6 Winston R. Principles of solar concentrators of a novel design. *Solar Energy* 1974; 16: 89–95.

7 Rabl A. Comparison of solar concentrators. *Solar Energy* 1976; 18: 93–111.

8 Rabl A. Optical and thermal properties of compound parabolic concentrators. *Solar Energy* 1976; 8: 497–511.

9 Welford WT, Winston R. *High Collection Non-Imaging Optics*. New York: Academic Press, 1989.

10 Williamson DE. Cone channel condenser optics. *Journal of the Optical Society of America* 1952; 42: 712–715.

11 Nilsson J. Optical design and characterization of solar concentrators for photovoltaics. Licentiate thesis. Lund, Sweden: Lund University, 2005.

12 . Kaplan GM. *Understanding Solar Concentrators*. Technical Paper # 30, Volunteers in Technical Assistance (VITA), 1985.

13 Scartezzini JL, Courret G. Anidolic daylighting systems. *Solar Energy* 2002; 73: 123–135.

14 Simone CM, Courret G, Paule B, Michel L, Scartezzini JL. Design of anidolic zenithal light guides for daylighting of underground spaces. *Solar Energy* 2001; 69: 117–129.

15 Perez R, Reals R, Michalsky J. Modeling skylight angular luminance distribution from routine irradiance measurements. *Journal of the Illuminating Engineering Society* 1993; 22: 10–17.

16 Taengchum T, Chirarattananon S. *Ray tracing method for simulating daylight transmission through tubular light pipes with anidolic concentrator: Proceedings of the 5th International Conference on Sustainable Energy and Environment (SEE 2014): Science, Technology and Innovation for ASEAN Green Growth,* Bangkok, Thailand, 19–21 November 2014.

17 Hinterberger H, Winston R. Efficient light coupler for threshold Cerenkov counters. *Review of Scientific Instruments* 1966; 37: 1094–1095.

18 Kalogirou S, Eleflheriou P, Lloyd S, Ward J. Low cost high accuracy parabolic troughs construction and evaluation. *Renewable Energy* 1994; 5: 384–386.

19 Smestad G, Ries H, Winston R. The thermodynamic limits of light concentrators. *Solar*

Energy Materials and Solar Cells 1990; 21: 99–111.
20 Pereira M. *Design and performance of a novel non-evacuated 1.2x CPC type concentrator: Proceedings of Intersol Biennial Congress of ISES*, Montreal, Canada, 1985.
21 Kittler R, Perez R, Darula S. A set of standard skies characterizing daylight conditions for computer and energy conscious design, US SK 92 052 Final Report, ICA SAS Bratislava, Bratislava: Polygrafia, 1998.