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Nonimaging Reflective Lens Concentrator

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ABSTRACT

A new rear-focus concentrator design based on an array of mirrored elements is presented. Both axisymmetrical and linear optical configurations are discussed. The new design allows for relatively uniform target/receiver illumination without the use of secondary optics. It ideally suits for concentrating PV modules with geometrical concentrations above 20 suns in a linear configuration and above 1000 suns for a point focus system. The proposed devices can also be used for high-temperature furnaces and hydrogen production applications to deliver highly concentrated fluxes ($>10^3$ W/cm^2) directly to the reactor saving on the heliostat efficiency losses and costs. Results of prototyping and testing of several linear-focus PV concentrators based on this concept are also presented.

1. Introduction

The recent developments in concentrating photovoltaics (CPV), where refractive Fresnel lenses have been used almost exclusively, have created a strong demand for advanced rear-focus concentrating optics. Besides reducing the consumption of PV materials, the concentrator approach allows for entering the domain of highly efficient multi-junction cells which have already demonstrated a record efficiency of 37% under concentration [1] and have a potential of even further growth [2].

On the other hand, very high concentrations are needed to make these high-end cells cost competitive with conventional Si solar cells. While it has been demonstrated that advance cells can effectively work at 1000 suns and above (see, e.g., [3]), the Fresnel lens technology matching these needs is yet to be developed.

In this paper, we introduce a new concept of non-imaging reflective lens (NIRL) concentrators which may enhance the efficiency and utility of many solar concentrating technologies by combining the high collecting power of mirrors with the design flexibility of lenses.

2. Reflective Lens Approach

The reflective lens uses an array of concave, spaced apart reflectors inclined at relatively sharp angles with respect to the incident sunlight. Each element in the array is designed to reflect the corresponding portion of the incident radiation downward through the space between itself and an adjacent reflector and direct it to a common focus (Fig. 1). As it is shown in [4], with the appropriate alignment of the reflectors, the radiation can be concentrated using only a single reflection and without any energy spillage.

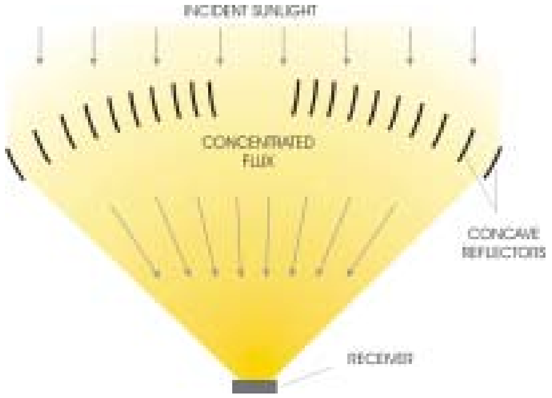


Figure 1. NIRL optical concept.

In order for such a system to work as an energy collector, the profiles of individual reflectors are typically curved to a parabolic or circular shape. However, at this geometry of reflection, the required concavity of most reflectors is rather small which ensures that the profiles can be of almost any concave shape, provided that they have the appropriate curvature for reflected rays convergence at a common target [5]. Indeed, this system will form no image regardless of the reflector shapes, since the target is illuminated by a superposition of several concentrating beams formed by respective reflectors.

The multi-element approach is inherently flexible and adaptable to specific applications. For example, with the use of raytracing, NIRL can be designed to provide either a maximum concentration by centering all concentrated beams at a common focus or a relatively uniform target illumination by making the individual concentrated beams partially overlapping at the focal area.

While employing a segmented collector aperture which is common to all Fresnel-type optics, this system uses a single-stage specular reflection to form the focus on the rear of the concentrator. As a result, the concentration ratios achievable with NIRL can significantly exceed those of an equivalent refractive lens for a broad spectrum of system designs.

3. NIRL Designs

Similarly to a Fresnel lens or most other concentrators, NIRLs can be designed in a point focus or linear focus configuration.

The axisymmetrical NIRL is also called the Ring-Array Concentrator (RAC) since it consists of an array of concentrically nested conical rings. The rings can be interconnected by radially extending support ribs to form a rigid structure (Fig. 2).

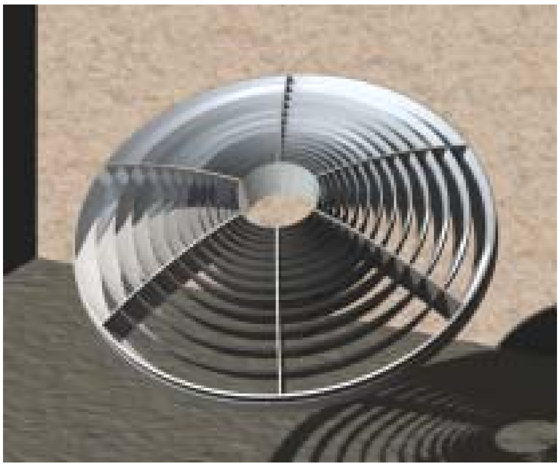


Figure 2. Ring-array NIRL.

This concentrator can deliver very high concentrations outperforming even the parabolic dish at shorter focal lengths [6]. Figure 3 shows a theoretical irradiance distribution obtained from analytical calculations for a ring-array concentrator having the diameter of 1 meter and based on non-imaging parabolic ring profiles. This distribution was obtained for a "no-loss" approximation. No design optimization for obtaining the highest possible concentration was done in this calculation, however.

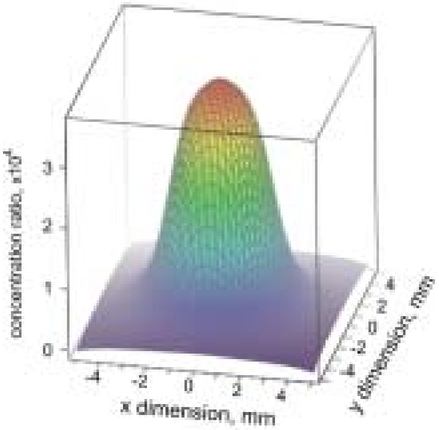


Figure 3. Theoretically calculated flux map for an array of nested parabolic rings.

A line-focus version of NIRL, also called the Slat-Array Concentrator (SAC), can be formed by an array of straight and relatively narrow reflective slats aligned along a common longitudinal axis. Figure 4 shows one of the possible designs of SAC with the slats incorporated into a frame together with a narrow-strip PV receiver.

This configuration can be used with single or dual axis tracking. In case of one axis, the longitudinal dimensions of the design can be extended to any desirable length similarly to the parabolic trough mirror.

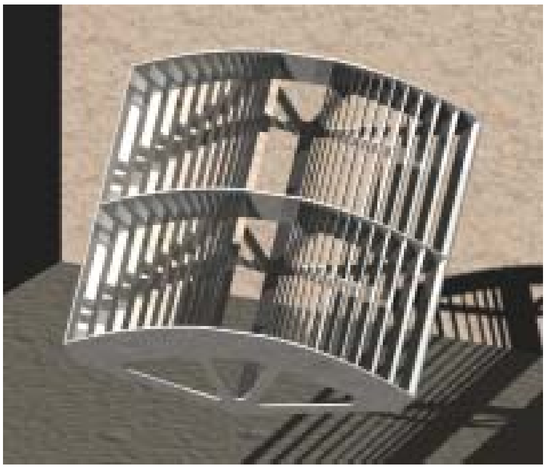
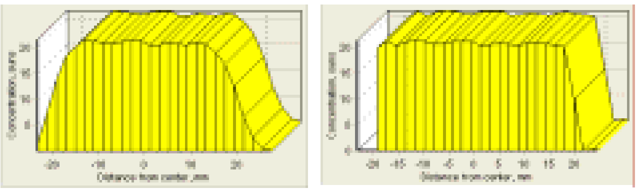


Figure 4. Slat-array NIRL.

Arranging the concentrator aperture as an array of independently positioned slats brings several design advantages with regards to shaping the concentrated beam to a desired irradiance profile on the receiver. One such possibility can be realized by aligning the slats so that their individual focal lines become slightly displaced relatively to each other forming a more uniform concentrated beam. This can be useful for photovoltaic applications where the uniformity of concentrated beam is necessary for obtaining optimal conversion efficiencies.

Figure 5 illustrates the degree to which the concentrated flux can be homogenized by using this technique. Only one half of the symmetrical SAC was used for this demonstration. Figure 5a shows the irradiance distribution obtained from raytracing for an array of 14 identical slat reflectors. Despite the reflectors were designed to have circular profiles for simplicity, the obtained distribution is almost flat across the receiver. Figure 5b shows the irradiance profile for the same array but with a simple secondary homogenizer which improved the uniformity even further. The homogenizer was designed as a pair of planar and very narrow mirrors to intercept only about 5% of the concentrated flux at the edges of the receiver. In this case, its contribution to the system losses is negligible, unlike the systems where secondary optics is used to redirect the entire flux coming from the primary.



a) b)

Figure 5. Irradiance profiles of linear NIRL optimized for flux uniformity.

4. Proof-of-concept Prototyping

Several prototypes of the linear NIRL have been built in order to verify the optical concept and raytracing calculations. Most prototypes were designed as concentrating photovoltaic modules which also allowed to independently assess the optical efficiency from electrical tests.

Figure 6 shows a concentrator prototype based on the asymmetric SAC designed for 40X geometrical concentration. In this prototype, we used an array or arc-shaped slats optimized for improved flux uniformity and hot spot removal [7].

Figure 6. 40-suns CPV.

A larger CPV prototype based on two asymmetric modules assembled on a lightweight frame was also built and mounted on a two-axis tracking platform (Fig. 7).

Figure 7. 20-suns CPV module.

This system was designed for 20 suns concentration and 500W peak power capacity. The shape and dimensions of slat reflectors were calculated from raytracing and the same optimal circular shape was used for all slats. A flux map obtained for this concentrator using digital imaging and a lambertian target is shown in Fig.8.

The concentrator efficiencies measured for different prototypes using optical and electrical tests were between 85% and 89% at the mirror reflectance being from 89% to 92% [7]. The test systems have also shown a good stability of the focal spot up to the tracking errors of 0.3° in elevation.

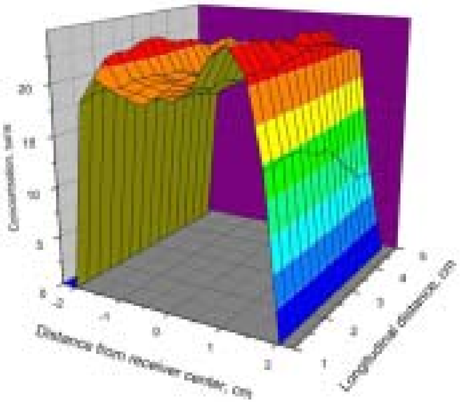


Figure 8. Irradiance profile measured in the focus of 20-suns linear NIRL.

5. Discussion

Published research suggests that most of the advanced lens-based CPV modules developed to the date are designed for the concentration ratios of 250-500 suns and 15-20 suns for the point focus and linear focus configurations, respectively. The requirement of higher concentrations puts excessive pressure on the lens design since the concentrating ability of Fresnel lenses is constrained by the fundamental limits of refractive optics. As a result, further advancements of Fresnel lens technology are typically relying on secondary concentrators which reduce the overall optical efficiency while the performance still remains capped at lower than desired concentration levels.

It can be seen from Fig. 3 that the geometrical concentrations well above 10^4 suns are possible with the concentric NIRL design. This provides almost two orders of magnitude cushion for the future growth of CPV concentrations compared to the refractive lenses. As the so high flux densities can be obtained on the back of the concentrator, the design can be seamlessly integrated into a variety of next generation solar technologies.

A mid-size or mini-version of the device can be used for constructing ultra-high concentration CPV modules without the second-stage concentrators. It should be noted that, as was demonstrated in Fig. 5, simple secondary optics can still be used for fine adjustments of flux uniformity. Obviously, the NIRL design can be tailored to bring its maximum concentrating power down to the currently required levels of 1000 to 2000 suns for the optimal CPV performance.

The linear-focus NIRL can be used for developing next-generation CPVs employing high-efficiency crystalline silicon cells which have already reached 26% in conversion efficiency. The experimental PV concentrator shown in Fig. 7 demonstrated a fairly low module weight of about 10 kg/m^2 which is about the weight of today's flat-plate PV panels suggesting that this CPV approach can be very competitive in production.

Some interesting possibilities exist regarding the use of the ring-array design in high-temperature furnaces and water splitting reactors for hydrogen production. Our estimates show that if at least 30% of the maximum theoretical concentration is reached in practice, flux densities above 1000 W/cm^2 and temperatures of 2500-3000°C can be easily realized in a reactor disposed below the concentrator using a single-stage concentration. Additionally, if the concentrator is mounted in such a way that it is rotated around its focal point for tracking purposes, the need of a heliostat, which is often utilized in solar furnaces, can be eliminated.

6. Conclusions

The reflective lens is a new conceptual design for solar concentrators. It appears to be the only design which can provide ultra-high single-stage concentrations and flux uniformity on the rear of concentrator.

The proposed reflective lens concept fits easily into the configurations of existing solar concentrating devices where Fresnel lenses have traditionally been employed, while substantially extending their capabilities. Particularly, mini-CPV modules operating at 1000 suns and above can be created without the optical losses and cost overhead associated with secondary optics.

Several first-of-a-kind reflective lenses have been built and tested. The tests conducted for linear-focus NIRL prototypes have shown a good agreement of theoretical calculations and computer-based raytracing with the measured flux maps. The measurements also confirmed that the optical efficiency of rear-focus reflectors is comparable to that of retro-reflecting mirrors such as parabolic troughs and dishes.

It should be noted that the new solar optics described in this paper is much more general than the example designs shown. The designs may need to be altered and possibly further improved to fit particular applications and obtain maximum benefits from the new concept. However, the theoretical assessment of NIRLs strengthened by very encouraging early prototyping and test results prompts for considering this approach for a broad range of solar technologies. The concentrating photovoltaics alone has made so dramatic progress in the recent years that, perhaps, a single breakthrough boosting the sunlight collection power may significantly shorten the time it needs for entering the rooftop and utility-scale markets.

7. Acknowledgements

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8. References

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