# DESIGN AND FABRICATION OF A SOLAR COLLECTOR FOR DAYLIGHTING SYSTEMS BASED ON HELIOSTAT LAYOUT


## Abstract

The present research proposes a non-imaging concentrator system based on heliostat layout for a daylighting collector. The system consists of small planar mirrors in a modular array operating as a passive solar optical aperture. To simulate and optimize the layout and alignments of the mirrors and to prevent optical losses, a graphical algorithm for the central receiver system is utilized. This radially staggered arrangement is designed with the help of the backward ray tracing concept to achieve a high concentration factor. The accuracy of backward ray tracing has been demonstrated by the forward method. To verify the accuracy of the numerical results, prototypes have been fabricated based on the optimized solution and have been subsequently assessed under solar radiation and a laser setup. The sensitivity analysis is thereafter performed to calculate the sensitivity of the proposed design to the manufacturing inaccuracies. Evaluation of the experimental results obtained for the geometrical concentration ratio shows that the proposed modular daylighting collector has potential application in daylighting for buildings.



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**Keywords**

Solar collector, concentrator collector, solar optical aperture

## Introduction

The issue of reducing overall electricity load is currently the most critical challenge that building lighting industries are facing. Therefore, several experimental and numerical researches have been carried out to solve this difficulty with proposing different optical daylighting systems. These technologies are divided into two types, namely vertical lighting systems (VLS) and horizontal lighting systems (HLS). A number of these studies have concentrated on the VLS. Due to the steep light profile (SLP) and overshadowing problems, VL Systems are not efficient for a deep-span building or dense urban area with less sky exposure angle (Kim & Kim, 2010). Besides, permission for construction extension in both plan and elevation overrides the essential demand for lighting, which can also lead to the inevitable use of HLS (Khosravi et al., 2014).

In general, collectors used in HL Systems are transparent optical collectors, which can be classified roughly into two main categories, namely the ones composed of compound aspheric lenses (True, 1987) and reflector collectors (Goldenberg, 1990; Goldenberg & Winston, 1990; Welford, 1989), whether in the passive or active mode, including: Mangin collectors, conic Cassegrain collector (Sansoni et al., 2009), Fresnel lens (Ullah & Shin, 2012; Tsangrassoulis et al., 2005), spherical, and aspherical mirrors (Ciamberlini et al., 2003; Schlegel et al., 2004). Most of the research on these concentrator collectors has received criticism due to the fact that they are not cost effective. Therefore, such limitations have impeded their mass production and widespread adaption.

In terms of luminous comfort, while reducing energy consumption, solar daylighting collectors coupled with optical fibers (Cariou et al., 1982; Gordon et al., 2004) are an efficient approach in areas with at least 4kwh/ (Taylor et al., 2014).

To satisfy lighting quality and reduce lighting energy consumption, this paper aims at designing and fabricating a climate-friendly, non-imaging concentrator collector (NCC) in non-tracking mode, given that a small target area can be set manually for annual optimal output flux.

The present paper proves that the suggested design is more cost effective than some optical designs presently developed and its manufacture is more feasible. The proposed collector is based on a graphical method from the central receiver system concept (CRS) (Mutuberria et al., 2015). It is a heliostat radially staggered arrangement to prevent blocking-shadowing losses over the year (Siala & Elayeb, 2001) and achieves an extremely high concentration ratio of solar radiation flux on a fixed receiver. In this concept, solar beams focused by means of the planar collectors are reflected toward a target which has been provisionally arranged for coupling with the fiber optic aperture at a narrower acceptance angle.

In this research, a ray tracing simulation for studying the mathematical design has been carried out. The computational algorithm was programmed using the MATLAB software. The code was used in connection with the program for the estimation of the hourly solar radiation and its direction.

To verify the accuracy of the results, a simple prototype has been constructed and evaluated in a real situation. In the first scaled model, 150 planar mirrors, each with a dimension of 0.5 cm by 0.5 cm, have been placed on a platform and planned in radially staggered arrangement. In addition to that, a simple setup has been designed to investigate the optical characteristic of the prototype in terms of stream convergence of direct beam under different solar angles.

The rest of the paper is organized as follows. In Section 2, a summary of the numerical techniques used to model the prototype is presented. Section 3 concerns with numerical results for luminance distribution and assessment. Finally, some concluding remarks are given in Section 4.

## Proposed System

Given the several ways in which light gathering can be achieved, it is apparent that an efficient daylight system is a low-cost focus collector with optimal concentration ratio that combines highly concentrated light in a very small area having minimal optical elements. Reaching the higher concentration ratio as a key merit function in smaller fiber diameters is the main target in collectors concentrating solar energy via optical fiber (CSEVOF) systems (Kandilli & Ulgen, 2009). This proposed collector could come up with a low-cost solution in the same manner as concentrated photovoltaic (CPV) to achieve high density of solar irradiation inside the aim point (Ullah & Shin, 2012; Xie et al., 2011).

### LAYOUT OF THE PROPOSED COLLECTOR

As noted earlier, the principle of a collection system was constructed based on radial staggered graphical layout. This method, suggested by Pylkkanen in 1993 to minimize optical losses, depends on shadowing, blocking, and spillage over the entire year. The configuration will differ regarding the lighting demand quantity and the overall targeted system performance. In this procedure, target height will determine the minimum radii of the field and twice mirror width is equal to minimum azimuthal spacing. According to graphical method principles, the radial and azimuthal spacing for other collector rings in the same group was calculated. A flowchart of the applied layout is given in Figure 1. By this means, passive and multi-seasonal collectors with multi-array mirrors have been designed. This stationary design must collect the division of solar rays related to the mirrors group. Therefore, each profile mirror has been used perpendicular or near perpendicular to the sun's rays with the angles at a particular period of a day. At any given time of the day, a certain mirror is always placed normal or near normal to the sun rays while the other mirrors keep on to collect radiation with decreasing levels of efficiency.

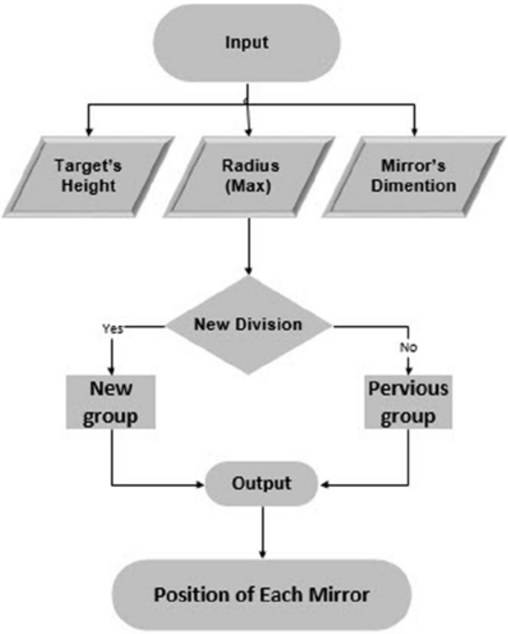


Figure 1: Flowchart of the mirrors field layout.

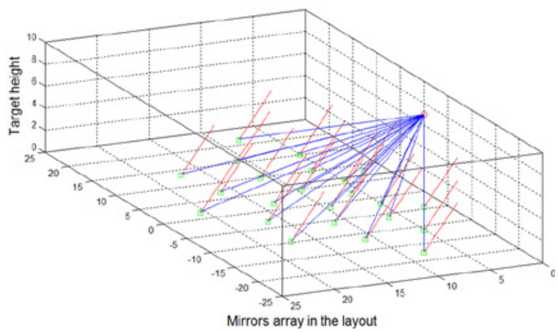


Figure 2: 3D design of the non-imaging flat concentrator mirrors. The configuration is for Month: June, Day number: 1, 6:00 AM, solar altitude: 13.4, latitude: 35.68 (Tehran latitude is 35 degree, 68 min).

### THE SOLAR POSITION MODEL AND THE MIRROR POSITION VECTOR

As mentioned before, a computational model for solar position and irradiation, although not as accurate as Solar Position Algorithm (SPA) (Reda & Nrel, 2008), is implemented which has the sufficient accuracy to compute the mirror normal.

In this model, the solar altitude and azimuth angles at any given location with latitude and any apparent solar time (AST) can be determined (Kalogirou, 2013; Eicker, 2011). The normal vector direction of each mirror is derived using Snell's law of refraction (Segal & Epstein, 2001). As the position of the sun varies, each mirror has been placed facing the sun for an exact period of time in a day based on the solar altitude and azimuth angle of a geographical location to ensure maximum concentration ratio as well as harvest the maximum possible energy by the proposed no tracking solar concentrator. Consequently, multi mirrors are divided considering solar altitudinal and azimuthal angles of latitude location, and into two categories for seasons, spring-summer collector and autumn-winter collector. Then, each group of collected rays must be redirected toward the optical fiber as the fixed target in the CRS group. As a result, the fiber optic must be set properly in the target area to redirect the maximum amount of solar beams toward the luminaire diffuser.

### Measurements, Analysis, and Discussions

For calculating and portraying the mirrors layout, the MATLAB software was used as the programming environment. A plot of these results is given in Figure 2, with the red rays and blue rays denoting the incident rays and the focused rays on to the target, respectively, and green squares acting as an optical aperture and demonstrating the center of the mirrors.

To analyze validation of numerical data, first of all, the proposed collector was built on a small scale. After that, a concentration ratio of that was analyzed under different controlled beams. The investigation of the scattered beam percentage at the target brought about the repetition of the manufacturing process.

In addition to the evaluation at a defined angle, the concentration and flux values were obtained under the sun ray. Time is an impediment for the experimental evaluation of all solar systems. For this reason, the evaluation is limited to the mirror for summer collector designed according to the division of summer solar data. Experimental data was analyzed without considering light guide system with an image processing method based on the CIE standard observer luminance efficiency to convert data measured onto 2D array (Feuermann et al., 2002). Figure 3 shows a redirected beam at the target surface (the numbers refer to each mirror). The luminance distribution function values for each part of the absorber area per pixel can be found in Figures 4–5.

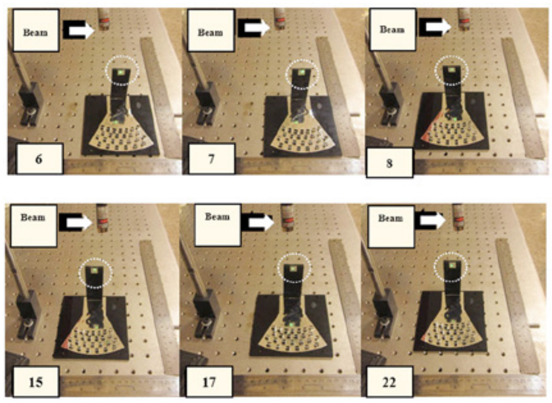


Figure 3: Redirected beam at the target surface. (The numbers refer to each mirror.)

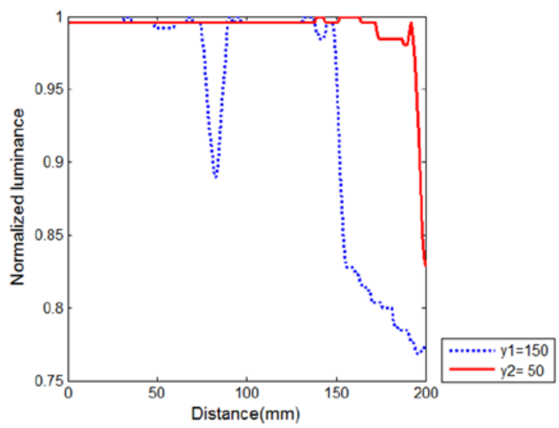


Figure 4: Prototype 1. Profile view of the relative luminance measurement on the target, t, Month: June, Day number: 1, 12:00 PM, solar altitude: 12, latitude: 35.68. The solid profile corresponds to the data for the 50 mm distance to target. The dashed profile corresponds to the data for the 150 mm distance to target.

According to Figure 4, the spot size of the received radiation at the absorber of the first prototype is bigger than the cross-sectional area of the target considering the horizontal axis as the X axis and the target center coordinates value is (x, y) = (100,100). As illustrated in Figure 5, the normalized luminance value of the target point area is roughly 1 and this quantity decreases to 0.78 at its corners.

As previously mentioned, the manufacturing process is repeated to coincide the spot size with the target area. According to Figures 6–7 the normalized luminance values of the target point area is equal to 1 and this quantity is 0 at other areas of the absorber plan. A subordinate concentrator can also be applied before the target position to boost the luminance.

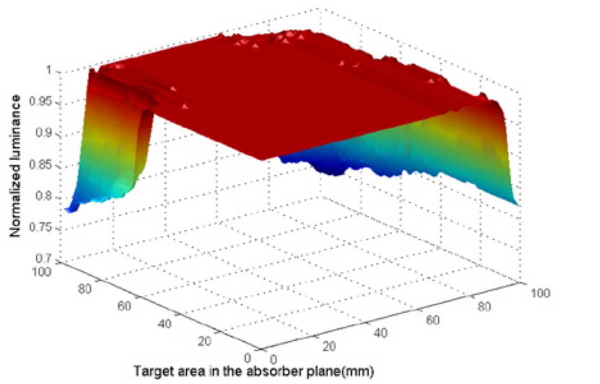


Figure 5: Prototype 1. Relative luminance map on the target, Month: June, Day number: 1, 12:00 PM, solar altitude: 12, latitude: 35.68.

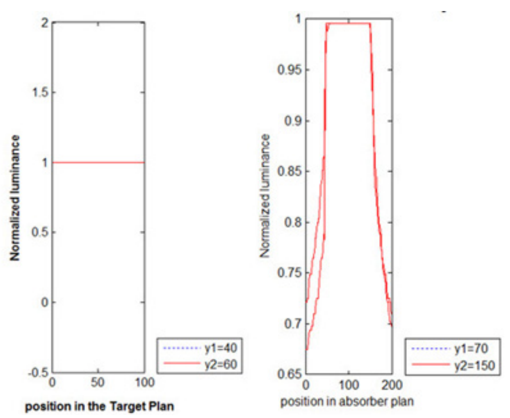


Figure 6: Prototype 2. Relative luminance measurement on the target and absorber plan, Month: June, Day number: 15, 12:00 PM, solar altitude: 12, latitude: 35.68. The solid profile corresponds to the data for the 40 mm and 70 mm distance to target. The dashed profile corresponds to the data for the 60 mm and 150 mm distance to target.

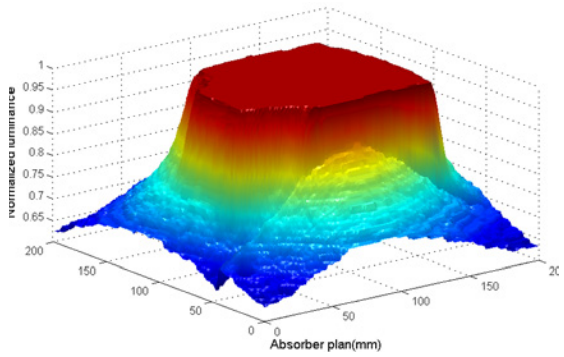


Figure 7: Prototype 2. Relative luminance map on the target and absorber plan, Month: June, Day number: 15, 12:00 PM, solar altitude: 12, latitude: 35.68.

To quantify the probability of rays that have been met, the target the Virtual Criterion Rating (VCR) (Inanici & Navvab, 2006) was calculated on the absorber plane provided that satisfying value for the normalized luminance is in the range [0.8–1]. The result showed that VCR value during mentioned test time (solar noon), is equal to 67%, which is increased as we add to the number of mirrors. As a result, the VCR is quite acceptable. The orientation, dimensions, and numbers of the module can vary in proportion to the luminaire size. A summary of flux measurement results for the selected prototype is provided in Table 1.

| Time | Solar altitude (degree) | Flux (watt hour per square meter) |
|---|---|---|
| 12 | 78 | 1.267749 |
| 13 | 71 | 0.740612 |
| 14 | 61 | 0.360691 |
| 15 | 49 | 0.102853 |
| 16 | 37 | 0.007358 |

Table 1: Prototype 2. Flux fluctuation on the target and absorber plan, Month: June, Day number: 15, solar altitude: 12, latitude: 35.68, Total area: 650 square millimeter.

If it is assumed that the experimental concentration factor remains constant by increasing the number of mirrors to a module having one square meter, the luminous flux will fluctuate from 1.5 to 27 kilo lumen.

To collect maximum solar direct radiations and minimize the total attenuation of the collector (losses per cosine, shadowing, blocking, air attenuation, and reflectivity effects), an array of seasonally optimized axes (the combination of seasonal optimal axes) is infinity preferable.

In addition, the sensitivity analysis was performed to achieve the requirement degree of precision and validate the result of the prototype's measurements. Error analysis showed that the relative error function would be 0.1 considering a basic parameters' relative error of 0.04 (slope and direction). Consequently, to concentrate the beams as the numerical model, the more precision in the manufacturing process must be considered. Obviously, a secondary concentrator can be used in order to decrease the construction requirements and improve the overall performance to maximize concentration ratio as those systems having SOE.

Considering credible CR value, the piping system must be set precisely in the target area to redirect the maximum amount of solar beams toward the luminaire diffuser.

As illustrated in Figures 8–10, the point focusing mirrors designed can be applied as net redirecting system, terrace's edge, and core rooftop systems in the following types of usage:

— The buildings with poor natural light in densely urban areas.
— The buildings without any aperture.

Correspondingly, the mentioned design can also be used to make concentrated photovoltaic systems produce more amounts of energy.

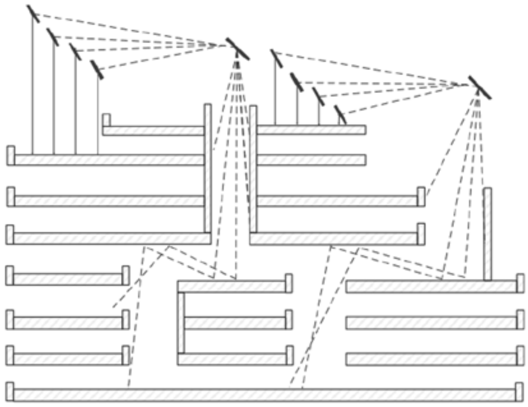

Figure 8: Net redirecting system (multi-tower design).

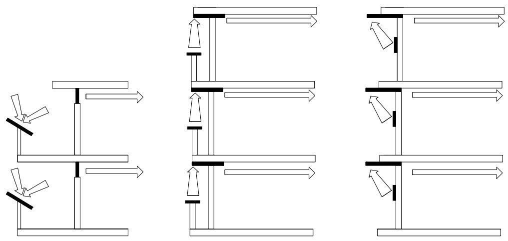

Figure 9: Terrace’s edge or facade installation.

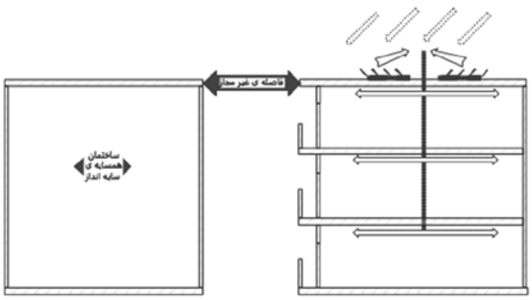


Figure 10: Core sun lighting system.

## Conclusion

In this research, we presented a collecting system based on the planar central receiver. According to the described numerical approach, a modular solar daylighting system was constructed. The collector was composed of small planar collecting units. Although the flat profile was theoretically less capable of concentrating, the non-spherical shapes and modularity resulted in the simplicity of manufacturing and their small size offered considerable reduction in wind and mechanical loading. In addition, because light-harvesting systems work with direct sunlight, the overall performance of the system in cloudy conditions was reduced. Consequently, it is highly recommended that these systems will only be used in climates receiving at least 4 watt hour per square meter. Moreover, to achieve an almost constant light intensity even in cloudy days, it is necessary to combine the diffuse radiation collecting unit and a secondary reflecting element with the proposed method. Evaluating the fabrication results of the final collector noticeably showed that the proposed multi-seasonal array design offers a high level of the concentration ratio which could be coupled into optical fibers. Despite having angular elements, the proposed collector unit is flush mount. However, due to the precision of the angles of the unit elements, a smooth surface and leveling is required in the installation process. Provided that the optical fiber serves as a fixed target, the suggested system will be restricted to multi-story buildings due to optical fiber losses. Although a semi-passive and tracking system has indicated better efficiency and performance, reliability, and uniformity of lighting throughout the solar span, it is beyond the scope of this research’s primary objectives due to pricing, life cycle, and maintenance cost by adding hardware and software requirements as well as movement elements. The resulting collector satisfied the project objectives but will, of course, serve as a platform for future work.

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