Design and optimisation of a light collector for the light emitting diode (LED) sources

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In these work we describe and optimise a number of light collector designs for light emitting diode (LED) sources. The tubular collector has been shown to be the most efficient configuration for LED light collection with an efficiency of over 86% when illuminated from top. Sidewall illumination with reflectors yielded an efficiency of 77% and dish configuration: 81%. The systems were optimised in ZEMAX using a Damping Least Squares (DLS) algorithm.

Nomenclature

R	=	tube/dish radius
d	=	wall thickness
a	=	shorter ellipse half-width
b	=	longer ellipse half-width
f	=	ellipse focus
D	=	distance between source and tube/dish entrance plane
α	=	illumination angle
φ	=	angle between ellipses of co-focal reflector
h	=	height
i	=	index
V	=	optimisation parameters' values
S(V)	=	merit function
T	=	target values in the merit function
W	=	weights in the merit function
A	=	Jacobean matrix of the merit function
G	=	gradient vector
I	=	identity matrix
	=	error vector
	=	merit function operands
p	=	damping factor

I. Introduction

THE purpose of optical system design is to produce, for a given optical system, a configuration that satisfies a set of specifications required by the envisaged application. Given a starting system, the software adjusts a set of variables in order to make the system as efficient as possible to achieve defined targets. The ZEMAX package for optical modeling is widely used for optimisation of commercial optical systems. In the current work we aim to design a chamber for the efficient collection of LED light on the surface. The key goal for the design is to maximise the efficiency of light collection in the chamber. The required level of irradiance depends then on the application. We will show that optimisation allows us to explore a variety of different configurations and allows us to show the problematic and beneficial areas of each.

The Damping Least Squares[1,2] (DLS) method was utilised in ZEMAX for variable optimisation. The merit function for DLS is a numerical representation of how closely an optical system meets a specified set of goals. In our case the goal is to achieve the best possible illumination in the chamber under industrial constraints.

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II. Model Parameters

To envisage optical modeling a set of appropriate parameters has to be chosen to reflect the real properties of sources, reflectors and future chamber prototypes. A number of conceptual designs have been modeled and optimised for LED illumination, including a tubular reactor illuminated from top, a tubular chamber illuminated from the side, and a dish illuminated from top. The key characteristics of the chamber components are shown in Table 1.

The chambers were designed for LED illumination. LED sources are utilised in a number of applications. The optical design of the light collector for these sources differs from that for laser diodes and solar-type sources. The source far field distribution is critical for optical design and optimisation as it determines angular intensity distribution, the maximum coverage area, intensity uniformity and source position. The ability to reproduce source far field in the model will increase accuracy of the model and hence will give realistic parameters as an output for design optimisation. To achieve high model accuracy with increased number of analysis rays we designed a ZEMAX model of the source LED based on experimentally measured data.

Component	Key parameters
Cylindrical tube	Outer diameter: 32 mm; wall thickness: 1.4 mm; length: 25 cm; material: glass
Reflector	Shape: elliptic and co-focal dual-elliptic; material: aluminum; reflectance: 82 %
Dish	Wall thickness: 1.4 mm; height: 5 mm; material: glass
Sources	LEDs; power: 1W; wavelength: 365 nm

Table 1. Characteristics of the reactor components.

We used "*LED Engin"* devices for initial experimental work and model verification. The source angular distribution is characterised by a viewing angle value, which is the off axis angle from the emitter centre line where the radiometric power is ½ of the peak value. The measured source angular distribution shown in Fig. 1 (red circles) for 1W LED source demonstrated good field uniformity with the viewing angles of 100 degrees. The measured angular distribution was used to model the radiant source in the ZEMAX software. The calculated angular distribution of the modeled source (blue), as expected, reproduced the experimental data to a high degree of accuracy.

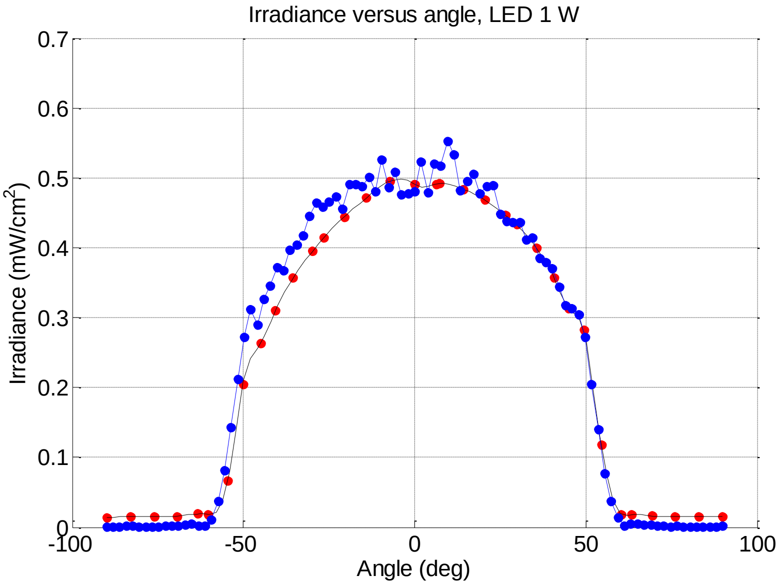

Figure 1: Measured irradiance versus angle (red circles) with a cubic spline interpolation (black line) and angular intensity distribution calculated from LED model (blue).

III. Damped Least Squares algorithm

For the optimisation of the system parameters we used the Damped Least Squares (DLS) algorithm provided with Zemax which is widely exploited in optical design. For that algorithm we introduce a merit function in the following way:

where is the current values of chosen parameters which will be discussed in the corresponding sections and is the weighting factor. Operands depending on the system parameters would be illumination of the detectors and are the target values. The goal is to minimise the merit function value.

We define the following: matrix with elements

gradient vector with elements

vector of change and error vector .

With these definitions, we have

If we assume that the changes in the operands are linearly proportional to the changes in the variables, we have

At the solution point, the gradient vector is zero, since the error function is at a minimum. The change vector is thus

These are called the least-squares normal equations, and are the basis for linear least-squares analysis. When nonlinear effects are involved, repeated use of these equations to iterate to a minimum often leads to a diverging solution. To prevent such divergence, it is common to add another term to the error function, which limits the magnitude of the change vector . In the DLS method, this is accomplished by defining a new merit function

A key property of DLS is that the minimum of is the same as the minimum of , since at the minimum, the change vector is zero. By differentiating and setting the derivative equal to zero at the minimum, we arrive at the damped least squares equation

which look like the normal equations with terms added along the diagonal. These terms provide the damping, and the factor is called the damping factor. This particular choice of damping is called additive damping, but more generally it is possible to add any terms to the diagonal and still maintain the same minimum.

IV. Light Collector Design

A. Tube collector illuminated from top

The tubular collector illuminated from top has shown to be extremely efficient in terms of optical illumination due to wave guiding. As the glass tube has higher refractive index than that of the air, the light rays entering the tube at small angles experience total reflection, and hence the majority of light entering the tube propagates inside it. The wave guiding makes illumination from top of tubular reactors highly effective with over 86 % of the source radiation propagating within the tube. Here the efficiency of illumination is the ratio of the LED power in the collector to the total source power. Optimisation of this configuration employs determination of source position for the optimal illumination angle, α. The parameters of optimisation are shown on the schematic diagram in Fig. 2b. The optimal distance between the tube entrance and the source, $D \cong R/\tan\alpha$, where *R* is the radius of the tube (*R*= 14.6 mm). To determine the optimal illumination angle we calculated and maximised total flux at the detector at the end of the tube, shown in Fig. 2a. Calculated results were as follows: *D* = 11.14 mm, α=52.65^0, efficiency 86.1%.

The merit function operands are the average flux on the detectors placed along the reactor tube. We maximised the flux on the detectors by varying the position of the source (i.e. illumination angle).

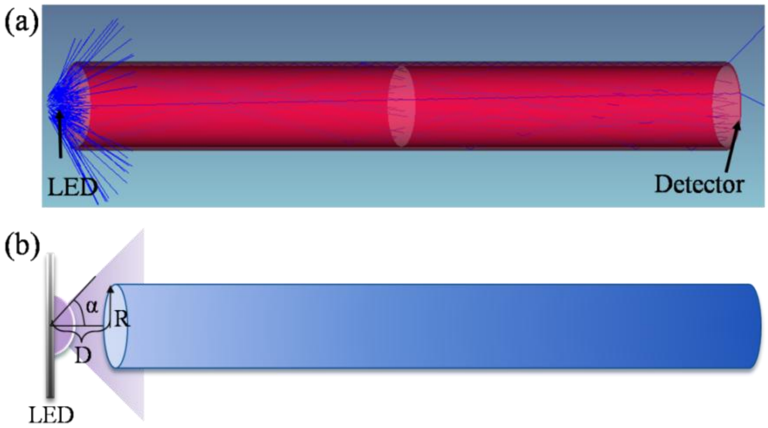

Figure 2: ZEMAX model (a) and schematic diagram (b) of the tubular cylinder illuminated from top.

B. Dish illuminated from top

Another modification of the cylindrical collector illuminated from top is a wide dish. The uniformity and conical profile of the LED far field with the viewing angle of around 100 degrees (the measured far field distribution of the LEDs is shown in Fig. 1) makes a disc-type surface one of the best configurations for uniform irradiation by the LED source. The 3D ZEMAX model of the wide dish illuminated form top is shown in Fig. 3. The optimisation of the dish and source configuration incorporates:

- Finding the optimal viewing angle, α
- Determination of the maximum dish size for the sufficient light intensity, R.

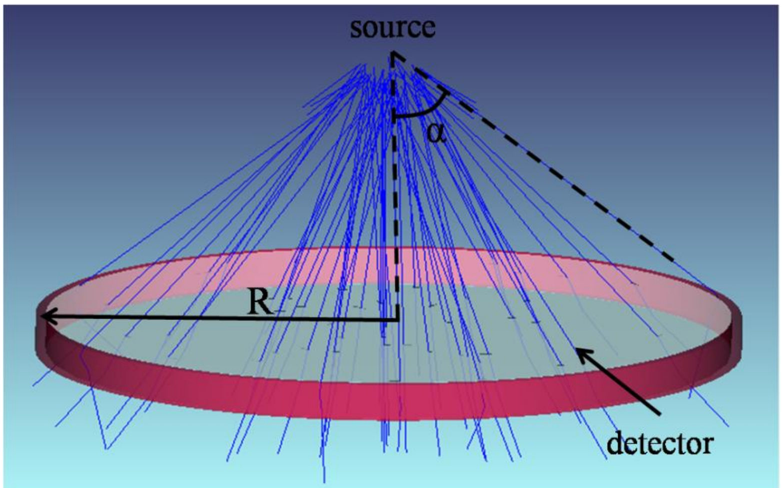

Figure 3: 3D model of the wide dish illuminated from top.

The optimized viewing angle, as expected, was similar to that for the tubular light collector We optimised the dish size and source position to have the largest dish diameter with the required minimum intensity level of 5 mW/cm^2 inside the dish. The maximum dish radius was R= 47.01mm ~ 47 mm, which resulted in ~70 cm^2 illuminated area via a single LED. The illumination efficiency was 81.4%.

C. Tubular collector illuminated from side

Optimisation of the tubular collector illuminated from side employs:

- Defining source position for the optimal illumination angle.
- Defining the maximum unit length for the sufficient irradiation.
- Configuration of LEDs for uniform irradiance.
- Design and optimisation of the reflectors.

The modeling optimisation results were as follows:

- Optimal illumination angle: $\alpha=53.27^0$; D=37.35 mm
- Unit length optimised for average intensity of 50 mW/cm^2: L= 48.89 mm~50 mm

These result in a UV-LED emitter configuration consisting of 5 LEDs placed within 50 mm from each other along the tube with 250 mm length, as shown in Fig. 4.

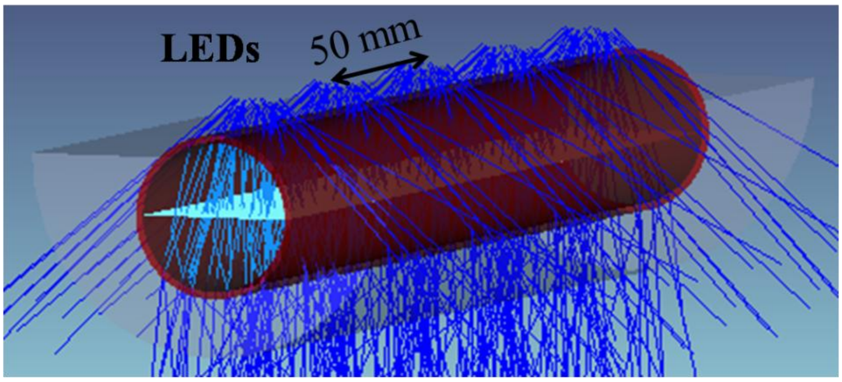

Figure 4: ZEMAX model illustrating configuration of LED sources.

D. Reflectors design and optimisation

The reflector shape is determined by the source and object configuration. The LED sources have a small footprint (7x7 mm) and a wide cone far field distribution. Therefore, they can be well approximated by a point source model. For the point source, the optimal reflector is elliptical, as it collects all the rays coming from the first focus point at the second focus, as shown in Fig. 5a. The focus points of the ellipse can be calculated from: $f = \pm\sqrt{b^2 - a^2}$, where a and b are smaller and larger ellipse half-widths, respectively. The ellipse parameters and focus points are shown schematically in Fig. 5b.

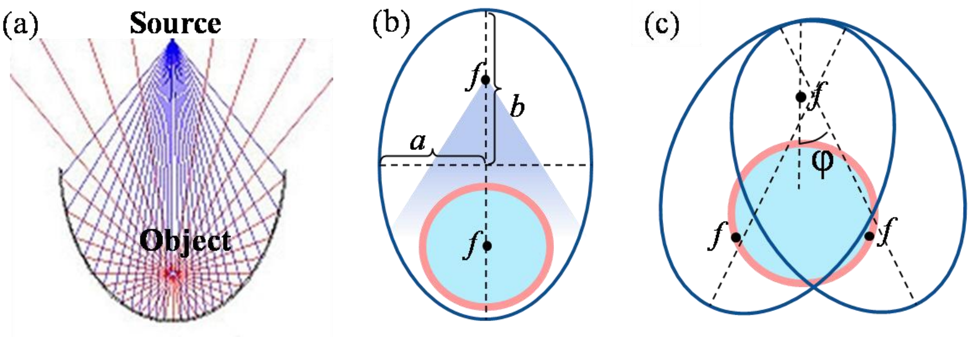

Figure 5: Schematic representation of the elliptic reflector (a), ellipse parameters (b) and co-focal dual-ellipse parameters (c).

A co-focal dual-elliptical reflector shown in Fig. 5c was also considered as an option for light collection. Besides optimising half-widths of the ellipses, one can vary the angle, φ, between ellipses. For effective illumination the LED emitter and the cylinder centre were placed at two focus points, as shown schematically in Fig. 5. By optimising the ellipse half-widths, a and b, one can define optimal shape and focal distance for the reflector to achieve maximum efficiency for light collection inside the cylinder and uniformity of the illumination. A set of detectors was placed in the middle of the tubular chamber as shown in Fig.6, with a large detector in the middle and two smaller detectors at the edges. To optimise the reflector shape we maximised the total flux at the large detector simultaneously allowing for sufficient power levels at the edge detectors.

The results of the reflector optimisation in the ZEMAX software were as follows:

- Elliptical reflector parameters: a=37.492; b=39.289; f=11.747
- Dual-elliptical reflector: a=34.945; b=37.068; f=12.365; φ=18.171°

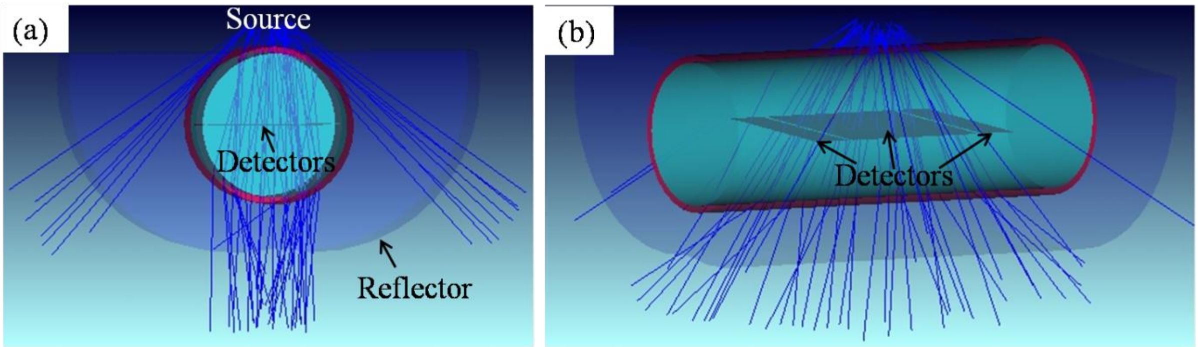

Figure 6: 3D ZEMAX models of the dual-elliptical reflector: front view (a) and side view (b).

With elliptic reflectors the average intensity level increased from 50 mW/cm^2 to 120 mW/cm^2, as shown in Fig. 7. The achieved illumination efficiency was 75%. However, refraction of the beams at the cylinder walls resulted in the regions with a weak power at the side walls (so-called “dead” zones). The beam propagation and refraction on the cylinder is shown in Fig.8.

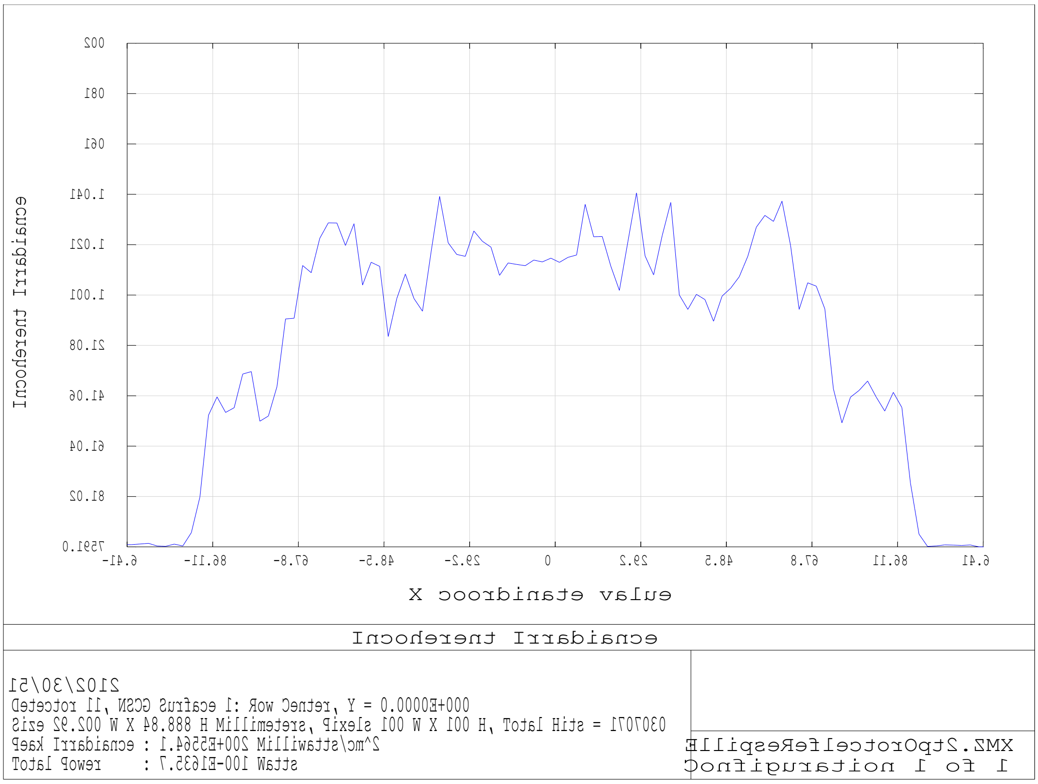

Figure 7: Irradiance distribution inside the tubular collector with elliptic reflector.

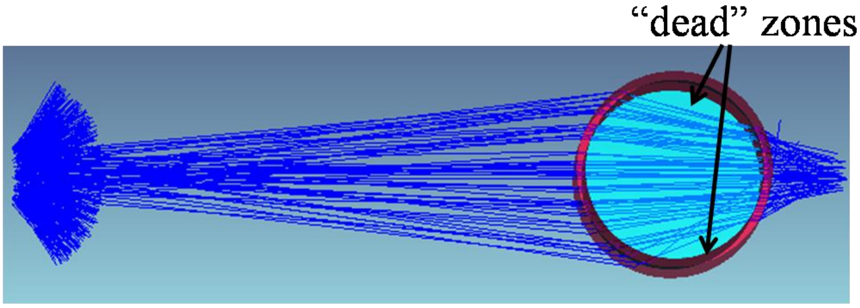

Figure 8: Beam refraction on the cylinder resulting in “dead” zones appearance.

Fig.9 shows irradiance distribution for the tubular collector with co-focal dual-elliptic reflector. The optimised dual-elliptical reflector also allowed achieving an average intensity level of 120 mW/cm^2, however, the illumination of the reactor was more uniform when compared to the elliptic reflector with the efficiency of 77%. The regions with the weak irradiance level due to beam refraction were still present.

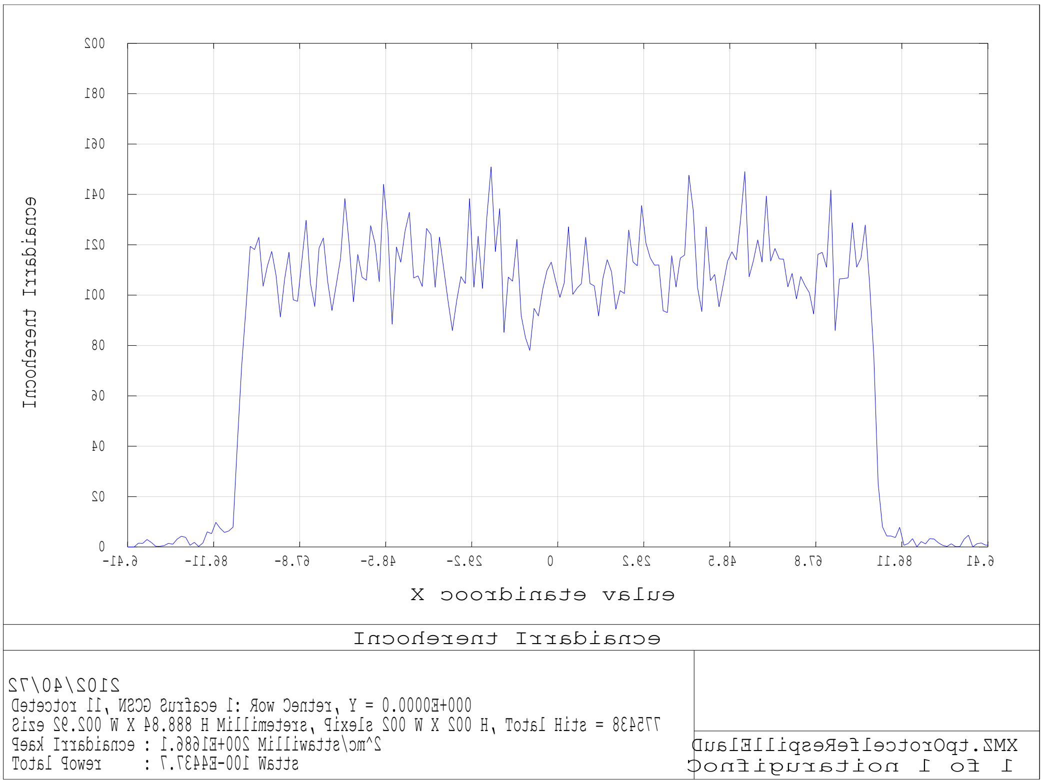

Figure 9: Irradiance distribution inside the tubular collector with co-focal dual-elliptic reflector.

V. Conclusion

A number of conceptual designs for LED light collector have been modeled and optimised using ZEMAX software. We designed the source model based on the experimentally measured far field distribution. The model was verified by comparison with measure data and accurately reproduced the source far field.

The tubular reactor illuminated from top has shown to be a promising option for illumination via LEDs, with an efficiency of 86% for the optimised source position. The dish design allowed for high a efficiency of 81.4%.

Illumination from the side required multiple LEDs for uniform intensity. Elliptical reflectors have been chosen for LED illumination due to their point source nature. Due to refraction of the beams at the cylinder walls the light intensity dropped dramatically at the side tubular walls. A design with an optimised elliptical reflector has shown to decrease the level of lost light with an increase in the average intensity from 50 to 120 mW/cm^2, with an efficiency increase to 75%. Dual-elliptical reflectors provided similar benefits with more uniform illumination. Regions with weak irradiance level were still present at the collector walls with reflectors.

Acknowledgments

We acknowledge funding from the European Union's Seventh Framework program managed by REA-Research Executive Agency. http://ec.europa.eu/research/rea ([FP7/2007-2013] [FP7/2007-2011]) under grant agreement n° [284461]

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