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Rotationally Asymmetrical Compound Parabolic Concentrator for Concentrating Photovoltaic Applications

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Abstract: This paper describes a novel type of solar concentrator – a rotationally asymmetrical compound parabolic concentrator (RACPC). The RACPC aims at addressing the following objectives: (i) to increase the electrical output of a concentrating photovoltaic (CPV) system by providing sufficient concentration gain; (ii) to minimise the usage of the PV material with the corresponding reduction of CPV system cost, and (iii) to eliminate the requirement of mechanical tracking by providing a wide field-of-view. This paper first provides a short review on variations of compound parabolic concentrator designs available to date. Next, the process of designing the RACPC is presented and the geometrical concentration gain of the concentrator is discussed. In addition, the optical concentration gain is also presented for various angles of incidence. Through simulations, it is demonstrated that the RACPC can provide significant optical concentration gains within its designed acceptance angle. An RACPC based system is an attractive alternative to conventional solar photovoltaic systems.

Keywords: solar photovoltaic; solar concentrator; rotationally asymmetrical compound parabolic concentrator.

Nomenclatures

θ_a	Half-acceptance angle
$\beta_{entrance}$	Flux (in W) at the entrance aperture
β_{exit}	Flux (in W) at the exit aperture
C_g	Geometrical concentration gain
C_{opt}	Optical concentration gain
$C_{opt\text{-}eff}$	Optical efficiency
d_0	Exit aperture width
d_1	Entrance aperture width
HTot	Total height of the concentrator
L_{PV}	Length of the PV cell
n	Refractive index
N	Number of extreme rays
W_{PV}	Width of the PV cell
2D	Two dimensional
3D	Three dimensional
ACPC	Asymmetrical compound parabolic concentrator
BICPV	Building integrated concentrating photovoltaic
CAD	Computer-aided design
CAP	Concentration-acceptance product
CCPC	Crossed compound parabolic concentrator
CPC	Compound parabolic concentrator
CPV	Concentrating photovoltaic
DTIRC	Dielectric totally internally reflecting concentrator
EPIA	European Photovoltaic Industry Association
IGES	Initial graphics exchange specification
PV	Photovoltaic
RACPC	Rotationally asymmetrical compound parabolic concentrator

1. Introduction

In the last decade, solar photovoltaic (PV) has attracted significant attention worldwide due to its promising potential in addressing the world's energy needs. According to a recent report by the European Photovoltaic Industry Association (EPIA), the cumulative installed capacity of solar PV stood at 136.7 GW at the end of 2013 [1], with a world distribution as illustrated in Figure 1. More than half of the installations contributing to the cumulative total were carried out in Europe, amounting close to 80 GW. A staggering 37 GW of new solar PV capacity was installed in 2013 – an increase in 35% when compared with the installations carried out in 2012 [1]. The leading market of new solar PV installations has shifted from Europe to Asia in the last year, with China and Japan as the top 2 countries that contributed to this new installed capacity with 11 GW and 7 GW respectively [1]. The rising number of solar PV installations in many countries has been mainly driven by the introduction of the feed-in tariff scheme [2]-[11]. It is reported that solar PV will continue its strong growth in 2014, with a projection of global expenditure on solar PV expected to increase by 45% in 2014 – reaching approximately $3.8 billion [12]. The solar PV market is dominated by crystalline silicon technology at 90% of the total share, with the remaining 10% contributed by thin film technology [13].

[Insert Figure 1 here]

Concentrating photovoltaic (CPV) is another technology that is employed to capture solar energy. The main aim of this technology is to reduce the cost of solar PV systems by minimising the usage of expensive PV material in the system design. This is achieved by incorporating an optical device that concentrates the sunlight onto a smaller area where a PV cell is attached [14]. By 2014 CPV contributes only with 357.9 MW to the total installed capacity - led by China and America [15]. However, according to GlobalData, the CPV market will 'expand dramatically' in the next few years, and is projected to reach 1GW in 2020 [15]. These installations are normally carried out in large solar power plant, but recently there has been a significant rise in the use of CPV for building integration applications including sky lights, double glazing windows and solar blinds [16]-[18]. This concept is widely known as building integrated concentrating photovoltaic (BICPV).

Researchers have produced various types of concentrators for CPV purposes [16],[19]-[30] . One of the most popular is known as the compound parabolic concentrator (CPC) and has been explored for various applications since 1960s [31]. The basic geometry of a CPC is shown in Figure 2. It can be divided into three parts; a planar entrance aperture (*AB*), two totally internally reflecting or reflective side profiles which consist of segments of parabolas (*AC* and *BD*) and an exit aperture (*CD*). The CPC has a half-acceptance angle[1] of θ_a and concentrates all the incoming sun rays within its half-acceptance angle to the exit aperture *CD* [31].

[Insert Figure 2 here]

To date, there is a variety of CPCs that have been studied (see Table 1). The two most common designs of CPC are the 2D linear [33] and the 3D rotational symmetry [34]. The 2D design is produced by extruding the cross section of a symmetrical CPC along the axis perpendicular to the 2D cross section - creating a square or rectangular exit aperture. As for the 3D rotational symmetry design, the 2D cross section design is rotated around the optical axis of the CPC which will have circular entrance and exit apertures. These concentrators can be fabricated from reflective materials such as mirrors or from solid dielectric materials. According to Welford and Winston [31], a concentrator fabricated using a solid dielectric material offers additional practical advantages such as ensuring 100% efficient total internal reflection on the side wall, producing a wider half-acceptance angle as well as creating a more compact concentrator.

Benitez et al. [35] indicates that the performance of any concentrator can be evaluated by using the concentration-acceptance product (CAP) formulae, which are defined as follow:

For the 2D design [35], the CAP is defined as

$$CAP_{2D} = C_{g(2D)} \ sin(\theta_a) \quad (2)$$

while for the 3D design [35], it is defined as

$$CAP_{3D} = \sqrt{C_{g(3D)}} \ sin(\theta_a) \quad (3)$$

where Cg is the geometrical concentration gain[2] and θ_a is the half-acceptance angle of the concentrator. The CAP value is governed by thermodynamic upper bound limit of equal to the value

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[1] The half-acceptance angle is defined as the angle where at least 90% of the rays entering the entrance aperture emerge from the exit aperture of the concentrator [16],[31].

[2] Geometrical concentration gain of a 2D concentrator is defined as the ratio of the width of the entrance aperture to the width of the exit aperture [31]. As for a 3D concentrator, this parameter is defined as the area ratio of the entrance aperture to the exit aperture [31].

of the refractive index of the material, *n*. In theory, a concentrator with a higher CAP value performs better than a concentrator having a lower CAP value. It is therefore desirable to have a design that has a CAP value closer to the value of index of refraction.

[Insert Table 1 here]

Ronnelid et al. [36] investigated the performance of a 2D extrusion of a symmetrical CPC fabricated from a reflective aluminium foil. The CPC has a geometrical concentration gain of 1.53, an exit aperture width of 14.4 cm, a total height of 12 cm and a half-acceptance angle of 35º. From the simulations, it was found that the CPC-collector could increase the annual energy output by 2.6% when compared with the non-concentrating system. This concentrator has a CAP of 0.88. Pei et al. [37] on the other hand, studied the performance of a 2D extrusion of a symmetrical dielectric CPC. The CPC has a geometrical concentration gain of 2.41, an exit aperture width of 1 cm, total height of 2.7 cm and a half-acceptance angle of 36.8º. It is calculated that the CAP of the concentrator is 1.44. Based on their experiments, they concluded that the introduction of a dielectric CPC increased the electrical power from 25.86 mW to 44.80 mW when compared with non-concentrating PV, an increment of about 73%.

Cooper et al. [38] utilised a reflective 3D rotationally symmetric CPC that has a half-acceptance angle of 30º. From their ray tracing analysis, they found that the transmission-angle curve of the reflective design produced an almost ideal step-like behavior within its designed acceptance angle. Goodman et al. [39] analysed the performance of a 3D rotationally symmetric dielectric CPC with a geometrical concentration gain of 6.1, a half-acceptance angle of 10º. The CAP is calculated to be 0.43. From the experiment, the cell coupled with this CPC design produced a 5.7 more short circuit current when compared with a bare solar cell.

Mallick et al. [40] also demonstrated another variation of a CPC design known as the asymmetrical compound parabolic concentrator (ACPC). Unlike the symmetrical 2D CPC, the two segments of the ACPC consist of two different lengths of parabola which allows the final design to have a wider acceptance angle. The concentrator has a geometrical concentration gain of 2 and is fabricated from a reflective material. Based on the experiments, their results point out that this concentrator managed to increase the maximum electrical output power by 62% when compared with a non-concentrating system – achieving a maximum optical efficiency[3] of 85.85%. Sarmah et

[3] An optical efficiency measures the fraction of the rays that is transmitted from the entrance aperture of the concentrator to the exit aperture of the concentrator [31].

al. [41] researched on a dielectric ACPC having a geometrical concentration gain of 2.8. Their analysis showed that the design has a maximum optical efficiency of 80.5% and increased the electrical power ratio to 2.27 when compared with a system without a concentrator.

Mammo et al. [42] constructed a reflective 3D crossed compound parabolic concentrator (CCPC)-based photovoltaic module. A CCPC is formed by intersecting two extrusions of linear symmetrical CPC orthogonally. With a geometrical concentration gain of 3.61, a half-acceptance angle of 30º, a total height of 1.616 cm and a square 1 cm by 1 cm exit aperture, this design is capable of generating a maximum electrical power concentration of 3 when compared to similar type of non-concentrating module. This concentrator has a CAP of 0.95. Baig et al. [43] fabricated the previous concentrator design by using a dielectric material known as polyurethane having a refractive index of 1.5, and evaluated its performance. The dielectric CCPC design has a maximum optical efficiency of 73.4%, a half-acceptance angle of 35º and produced a maximum electrical power ratio of 2.67 when compared with the non-concentrating design. As for the CAP, the value is calculated to be 1.09.

This paper proposes a new type of CPC design for use in BIPV systems. This concentrator is known as a rotationally asymmetrical compound parabolic concentrator (RACPC). Section 2 explains the steps involved in producing this design, and the geometrical properties of the RACPC are presented in Section 3. The optical concentration gain analysis is carried out in Section 4 to evaluate the angular performance of the concentrator. Afterwards, the annual output prediction of an RACPC based panel is presented in Section 5. Conclusions are presented at the end of the paper.

2. Design of the RACPC

The RACPC is a new variation of the CPC and can be constructed from dielectric material. The foundation and the algorithms to produce this concentrator are based on the concentrator design proposed by Ning et al. [28] for the dielectric totally internally reflecting concentrator (DTIRC). According to Ning et al. [28], the CPC is a specific case of the DTIRC family with a flat entrance aperture.

A MATLAB® based program has been developed to create the RACPC. The flow chart of the program is summarised in Figure 3 while the illustration of the creation process is presented in Figure 4. The RACPC design requires of the following input parameters: the total height of the concentrator, (*HTot*), the half-acceptance angle (θ_a), the length of the PV cell (L_{PV}), the width of the PV cell (W_{PV}), the trial width of the entrance aperture (d_1), the index of refraction of the material (n) and the number of extreme rays (N).

[Insert Figure 3 here]

[Insert Figure 4 here]

First, based on the input parameters, a 2D symmetrical design is produced (see position ‘1’ in Figure 4). The computer program calculates the trial height, which is later used to calculate the coordinates of the side wall of the parabola. This calculation takes into account a number of extreme rays entering the concentrator at the critical angle. Once it is completed, the program compares the trial entrance aperture to the calculated entrance aperture. The difference between the two apertures is used to adjust the trial entrance aperture. A number of iterations take place until the difference between both entrance apertures is within an acceptable error value. The calculated total height of the concentrator is then compared with the desired total height and is adjusted by varying the half-acceptance angle until the difference between the two total heights is within an acceptable error value. These steps will define the 2D design in position '1'. The process is repeated to get the next 2D cross-section design (see position ‘2’ in Figure 4). Each new design is computed by incrementing the angle of rotation of the cross-sections by 1^{o} and using the predetermined exit aperture value. The process stops when a 180^{o} rotation around the y-axis is completed. The program calculates three output parameters; the ‘final’ half-acceptance angle, the ‘final’ width of entrance aperture and the geometrical concentration gain of the concentrator. The program also saves all the coordinates of the design in a point cloud format for fabrication purposes.

The RACPC shown in Figure 5 is generated by selecting the total height *HTot* of 3.0 cm, a refractive index *n* of 1.5 and the exit aperture with dimensions of 1 cm by 1 cm. The geometry of the concentrator has distinctive features when compared with other CPCs. First, the planar entrance aperture has four axis of symmetry (see Figure 5(b)), unlike the 3D rotationally symmetry CPC or the CCPC which has a circular and square shape respectively. Another important feature of this concentrator is its square exit aperture, as presented in Figure 5(c). Sellami et al. [16] argued that the circular entrance and exit apertures of a traditional rotationally symmetry CPC exhibit losses which reduce the optical efficiency of the concentrator. They also indicate that from a manufacturing point of view, it is more desirable and easier to fabricate a square or a rectangular cell, which is widely available shape in the market, than a circular cell required in a rotationally symmetry design. The RACPC is also a variation of a 3D design, therefore it provides a higher geometrical concentration gain than the 2D linear CPC design of a symmetrical CPC.

[Insert Figure 5 here]

3. Geometrical Concentration Gain Analysis

This section investigates the effect of varying the total height and the refractive index of the concentrator on both the geometrical concentration gain and the half-acceptance angle of the RACPC. The geometrical concentration gain, C_g of a 3D concentrator is defined as the area ratio of the entrance aperture to the exit aperture of the concentrator [31]. It has been indicated in Section 2 that the MATLAB® program requires certain input parameters and returns three main output parameters which are the geometrical gain, the 'final' half-acceptance angle and the 'final' length of the entrance aperture. This information is valuable in estimating the final optoelectronic gain based on the input parameters as well as constructing and assembling the optimum RACPC design for BICPV applications.

Figure 6 shows some of the properties of RACPCs generated with various total heights and different refractive indices, where the variation of geometrical concentration gain and the half-acceptance angle are presented in Figures 6(a) and 6(b) respectively. From Figure 6(a), it can be observed that the geometrical concentration gain varies between 1.7299 and 6.5920. In general, the geometrical concentration gain increases as the total height of the concentrator increases. In Figure 6(b), the half-acceptance angle of the RACPC varies from 25.9183º to 55.3914º. From these observations, it can be concluded that when the height of the concentrator (and the gain) increases, the half-acceptance angle reduces. In terms of index of refraction, it can also be seen that both the geometrical concentration gain and the half-acceptance angle vary increase when the index of refraction of the material increases, as illustrated in Figure 6. For two concentrators with the same height, the one fabricated with a higher index of refraction has a higher geometrical concentration gain and larger half-acceptance angle. These three behaviours support the findings by Ning et al. [28] and Muhammad-Sukki et al. [19],[22]-[25].

[Insert Figure 6 here]

4. Optical Concentration Gain Analysis

Another important aspect to investigate is the optical concentration gain. The optical concentration gain, C_{opt} is defined as [16],[31]:

$$C_{opt} = \frac{\beta_{exit}}{\beta_{entrance}} \times C_g \quad (1)$$

where β_{exit}, $\beta_{entrance}$ and C_g are the flux (in W) at the exit aperture, the flux (in W) at the entrance aperture and the geometrical concentration gain respectively. The ratio of the flux at the entrance aperture to the flux at the exit aperture is also known as the optical efficiency, $C_{opt\text{-}eff}$ of a concentrator [34],[41]. In theory, any rays within the acceptance angle of the concentrator will emerge at the exit aperture of the concentrator [31]. The analysis evaluates the gain performance of the concentrator when exposed to rays at different angles of incidence. This is useful to predict the theoretical performance of the RACPC when exposed to the sun.

First, the 3-D surface coordinates of an RACPC are generated from MATLAB® in a point cloud format. This file is then imported into GeoMagic® software to produce a computer-aided design (CAD) model from which an Initial Graphics Exchange Specification (IGES) format file model is obtained, such as the one illustrated in Figure 5. Subsequently, this IGES file is imported into an optical system design software called ZEMAX® to conduct the ray tracing analysis. A simulation using any optical system design software such as ZEMAX® is better than using a programming software (i.e. MATLAB®) because [44]: (i) it gives flexibility in analysing any optical devices; (ii) it can analyse a greater number of incoming rays which results in better resolution of the optical flux distribution; (iii) it shortens the simulation times significantly, and (iv) it provides better result representations at the end of the simulation.

The setup for the ray tracing analysis in ZEMAX® is shown in Figure 7. A square light source is selected to produce one million collimated rays and is configured to produce an incoming power of 1,000 W. The IGES file of the RACPC is placed at a distance of 35 cm from the light source. To calculate the number of rays at the entrance and exit aperture of the RACPC, two photo detectors are attached at both ends of the concentrator. The simulation is carried out by first, firing the rays perpendicular to the concentrator where the number of rays at the entrance and exit apertures are calculated and recorded. This is repeated by increasing the rays' incidence angle by 5º until a maximum angle of 60º is reached.

[Insert Figure 7 here]

Figure 8 shows the optical concentration gain variation of several RACPC designs when the total height is varied from 2 cm to 5 cm and the refractive index is varied from 1.30 to 1.50. From the simulations, it is observed that the concentrator provides a substantial gain within its half-acceptance angle (in this example it can reach up to 6.18), and the optical concentration gain reduces when the angle of incidence is beyond the half-acceptance angle. A comparison between the half-acceptance angle values generated from the ZEMAX® simulation and the one generated from the MATLAB® simulations is presented in Table 2. Interestingly, the value of the half-acceptance angle obtained from the ZEMAX® simulations agrees with calculated half-acceptance angle from the MATLAB® simulation with a small percentage variation of between -0.32% and 7.62%. The CAP value is also calculated and included in Table 2. The CAP value is always less than the index of refraction and ranges between 0.88 and 1.32.

[Insert Figure 8 here]

[Insert Table 2 here]

It can be concluded that the trend of optical concentration gain is similar to the geometrical concentration gain analysis, where the optical concentration gain increases when the total height of the concentrator increases. This is also true in terms of the refractive index of the concentrator material, where the optical concentration gain is higher when the refractive index of the concentrator is higher for the same total height.

It is therefore pertinent to know that some trade off needs to be made when choosing the optimum RACPC design for the BICPV system. A higher gain is often desirable but this translates into a taller concentrator and smaller acceptance angle - this means that the RACPC design will only gather sun light for a shorter period of time during the day.

It is also important to investigate the variation of irradiance distribution on the solar cell when incorporating different RACPC designs. It has been reported by various researchers that an increase in concentration for a long period of time increases the temperature of the solar cell, and eventually reduces the electrical output of the system [25],[42]-[44]. Figure 9 shows the distribution of irradiance on the solar cell when three different RACPC designs having the same refractive index of 1.40 are simulated at normal angle of incidence. Based on the conditions indicated earlier in Section 4, a typical solar cell has a maximum peak irradiance of 16.7 W/cm^2, as illustrated in Figure 9(a). As for the RACPC, the irradiance distribution is concentrated at the four corners of the solar cell. The maximum peak irradiance reaches up to 70 W/cm^2, 90 W/cm^2 and 140 W/cm^2 when the total height of the RACPC increases to 3 cm, 4 cm and 5 cm respectively. This translates into an increment of 4x, 5x and 8x respectively when compared with the peak irradiance on a non-concentrating cell. It is therefore crucial for a BICPV system to have the right RACPC design and cooling system to ensure that the performance of the solar cell is at its optimum. If an RACPC design with higher gain is needed, the solar cell could be cooled by introducing a hybrid/thermal system (either using air or water), that utilises the co-generated heat to produce hot water and stimulate ventilation [19],[25],[45].

[Insert Figure 9 here]

5. Annual output prediction

It is desirable to predict the annual electrical output (in kWh) generated from the CPV system utilising the RACPC design and compare it with a conventional non-concentrating PV skylight. The comparison is carried out based on the area (in square meter) of solar cell used to produce a $1m^2$ PV skylight. One particular design of RACPC is chosen, with a total height of 3 cm and fabricated from a material with a refractive index of 1.5. Figure 10 shows an example of the CPV design that incorporates the chosen RACPC concentrator. To simplify the analysis, the following assumptions are made: (i) the solar cell conversion efficiency is 17.32%[4]; (ii) the panels are installed near the Malaysian Meteorological Department in Kuala Terengganu, Malaysia (5°22'48"N, 103°00’00”E); (iii) the panels are mounted on a south facing rooftop at an angle of 5^o from the horizontal to match the latitude of the site [46], and (iv) the panels are static, i.e. no mechanical tracking system is attached on any panel. Based on the average daily solar irradiance data in Kuala Terengganu, Malaysia [47], the variation of sun path throughout the year [46] and the daily optical concentration gain from the ZEMAX® simulation, the energy yield from both panels are calculated.

[Insert Figure 10 here]

Figure 11 shows the annual energy output from the RACPC panel and the conventional PV skylight. The RACPC panel produces 220 kWh per year, in contrast to the traditional PV skylight which only generates about 67.75 kWh per year. It can be seen that the RACPC based panel could increase the electrical output by 3.25 times (225%) when compared with amount generated by the non-concentrating counterpart. It is important to mention here that these calculations only predict the annual electricity output generated by the two panels.

Another advantage of the concentrator is that it could provide natural ambient light for building interiors due to the fact that the material used for the concentrator is transparent, which could potentially reduce the energy consumption and electricity cost for lighting purposes. Also, the cogenerated heat from the cooling system of the cell could be used for heating and/or to stimulate

[4] This is based on the efficiency of the cell used during the experiments carried out by Muhammad-Sukki et al. [24].

ventilation, which also reduces the electricity requirements in a building.

[Insert Figure 11 here]

Conclusions

A new type of concentrator, known as the RACPC has been created for use in BICPV systems. The steps to produce the RACPC have been discussed and both the geometrical concentration gain and the optical concentration gain are evaluated. From the simulations, it has been found that the RACPC could produce an optical concentration gain as high as 6.18 when compared with the non-concentrating cell depending on the half-acceptance angle. It can be concluded that a BICPV system incorporating this RACPC would not only generate electricity efficiently, but also minimise energy consumption in buildings by providing ambient light to building interiors, and using the cogenerated heat for heating and stimulating ventilation which could provide greener and sustainable building. The authors are currently fabricating a specific RACPC design to evaluate its actual performance.

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Figures and Tables descriptions

Figure	Description	Proposed size (width)
1	Cumulative solar PV installed capacity in 2013. Adapted from [1].	90mm
2	A cross section of a CPC. Adapted from [32].	90mm
3	The flowchart of producing an RACPC.	140mm
4	Demonstration of the angular rotation of the 2-D cross-sections to produce the RACPC.	90mm
5	An example of an RACPC (HTot = 3.0 cm and n = 1.30), where (a) is the isometric view; (b) is the top view; (c) is the bottom view, and (d) the side view of the concentrator.	140mm
6	Geometrical properties of the RACPC generated from various total heights and different refractive indices where (a) the geometrical concentration gain, and (b) the half-acceptance angle of the concentrator.	90mm
7	Ray tracing analysis conducted in ZEMAX®.	90mm
8	Optical concentration gain of various RACPC presented with various total heights and refractive indices.	140mm
9	Photodetector's results obtained from the ZEMAX® simulation of concentration distribution at the detector of (a) non-concentrating cell; (b) RACPC with $HTot$ = 3 cm; (c) RACPC with $HTot$ = 4 cm, and (d) RACPC with $HTot$ = 5 cm. All the concentrators are fabricated using n = 1.40. The unit is recorded in W/cm^2.	140mm
10	Aerial view of the arrangement of RACPCs in a module (not to scale).	90mm
11	Annual performance of the RACPC and the traditional PV skylight.	90mm

Table	Description	Proposed size (width)
1	Summary of various CPC designs that have been studied.	190mm
2	Comparison of acceptance angle values generated from the ZEMAX® simulation and from MATLAB® simulation.	190mm

Figure 1

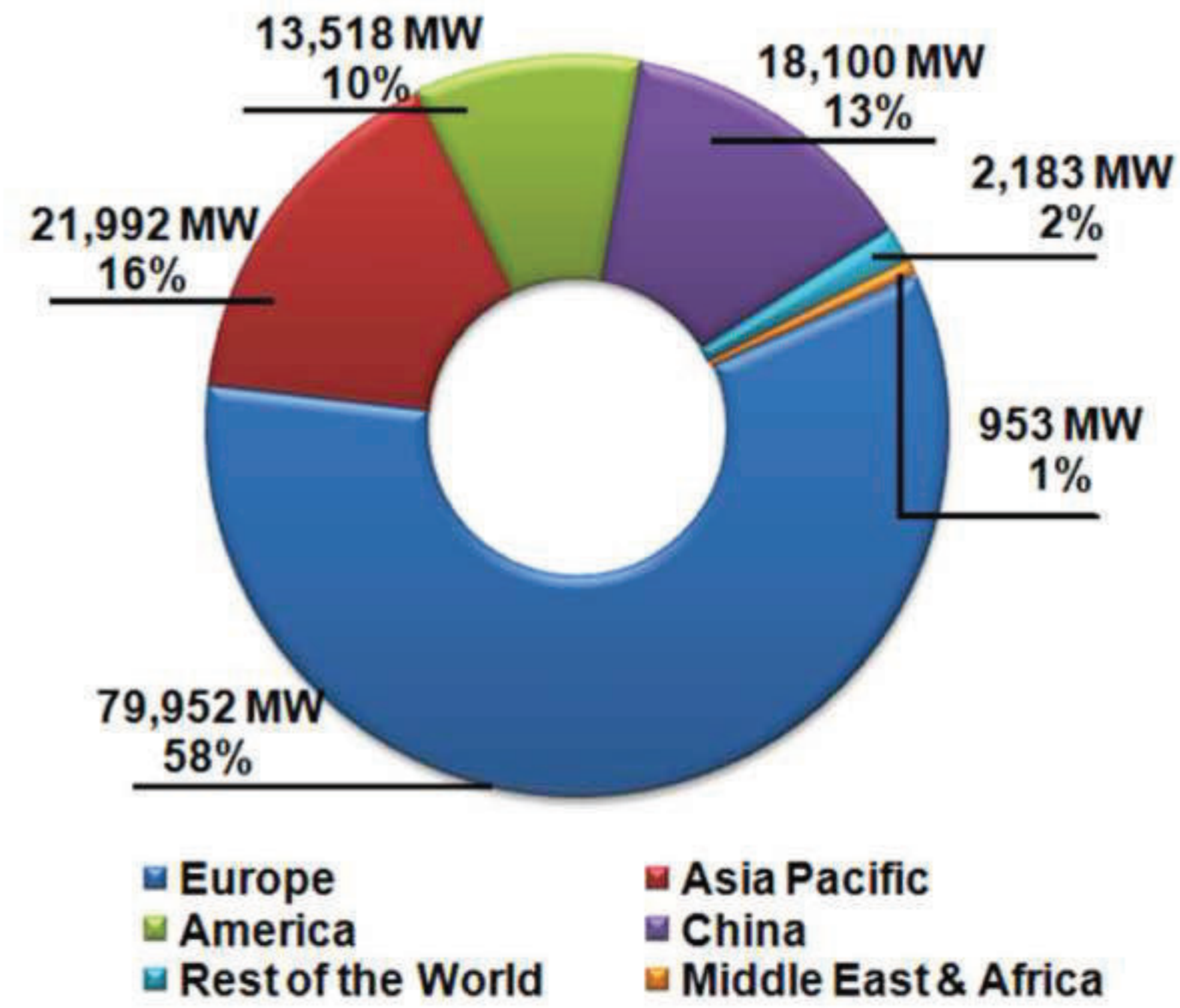
13,518 MW
10%
18,100 MW
13%
2,183 MW
2%
21,992 MW
16%
953 MW
1%
79,952 MW
58%
Europe
Asia Pacific
America
China
Rest of the World
Middle East & Africa

Figure 2

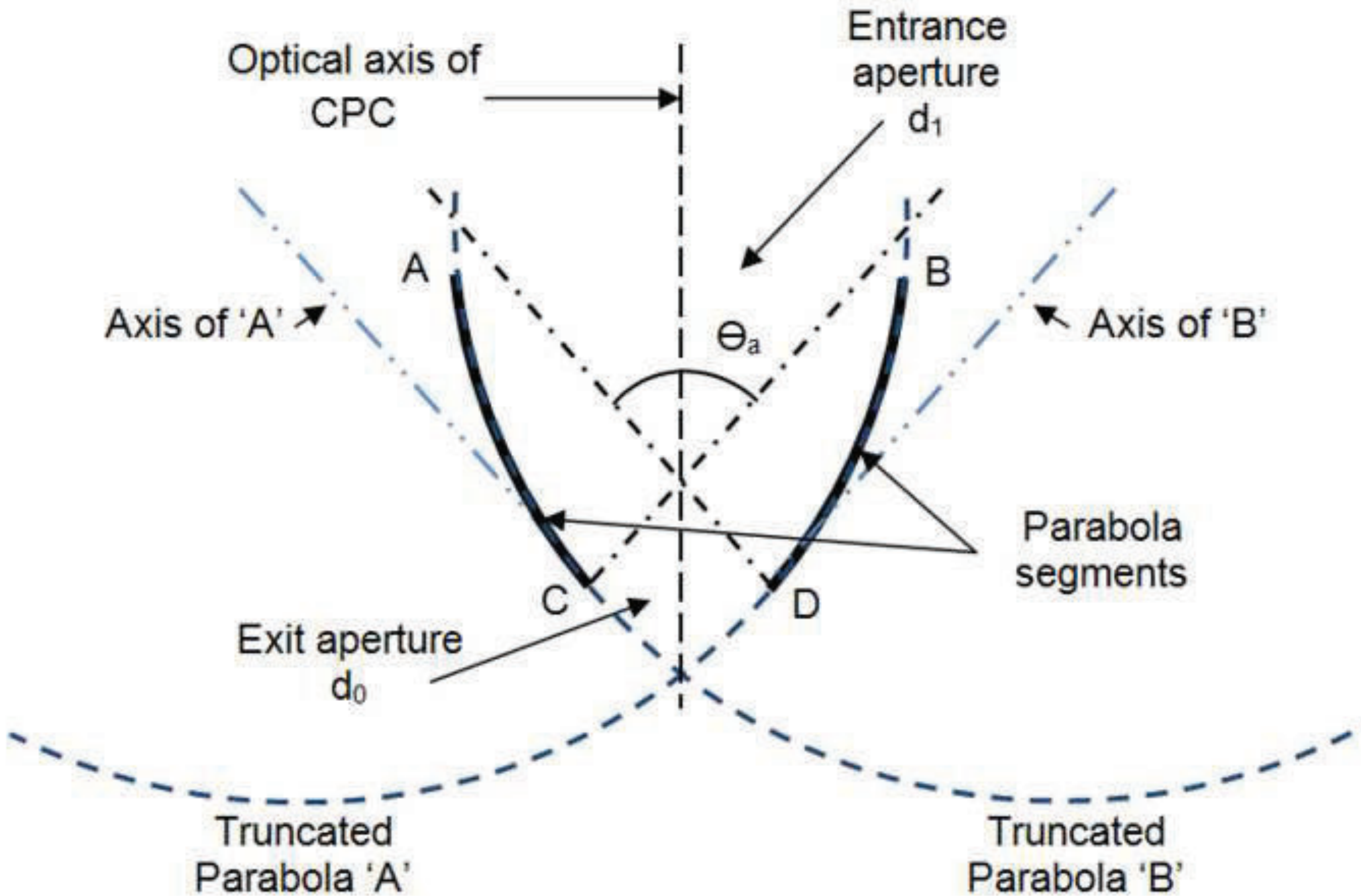
Optical axis of
CPC
Entrance
aperture
d1
A
B
Axis of 'A'
Axis of 'B'
Θa
Parabola
segments
C
D
Exit aperture
d0
Truncated
Parabola 'A'
Truncated
Parabola 'B'

Figure 3

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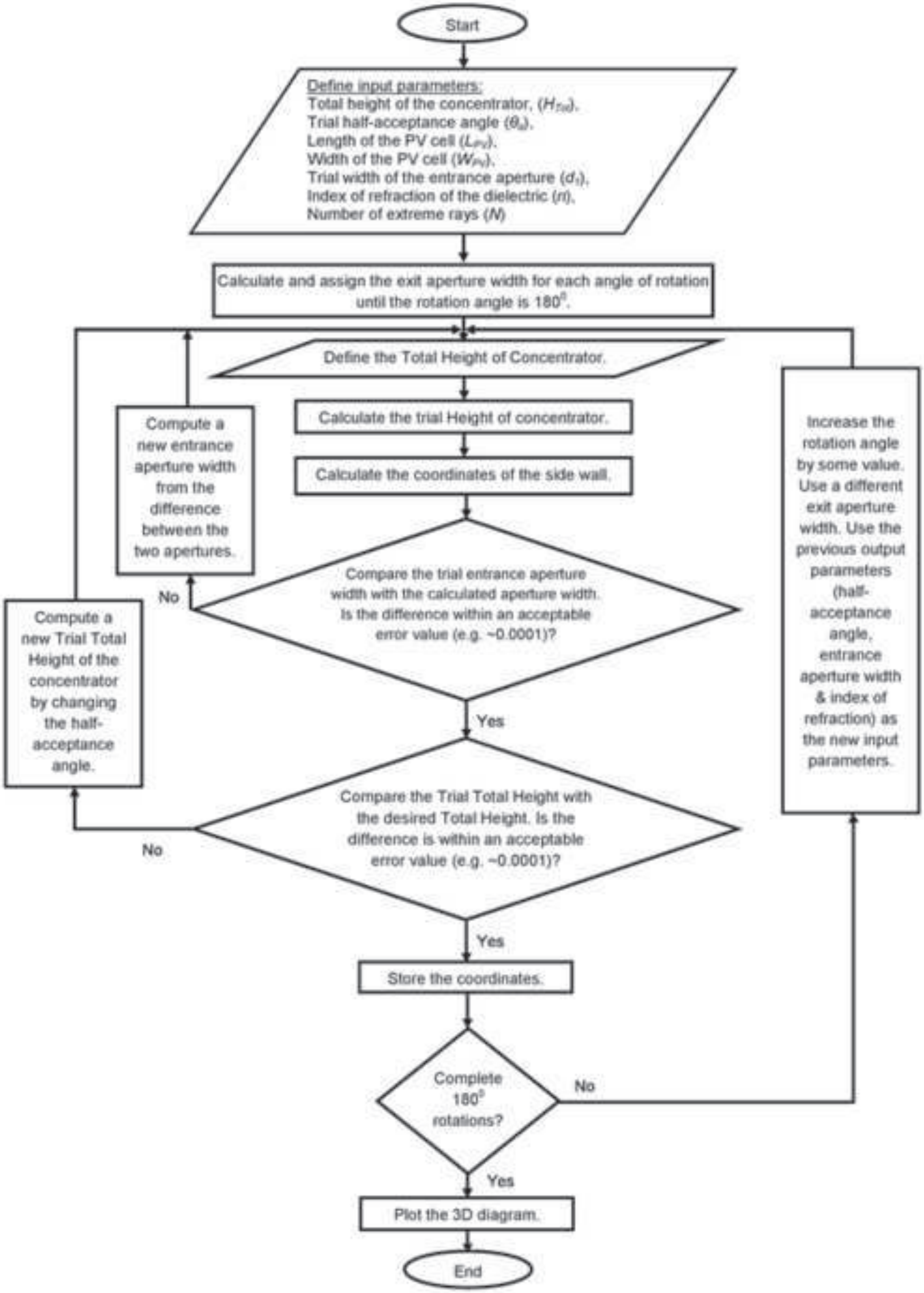

Figure 4

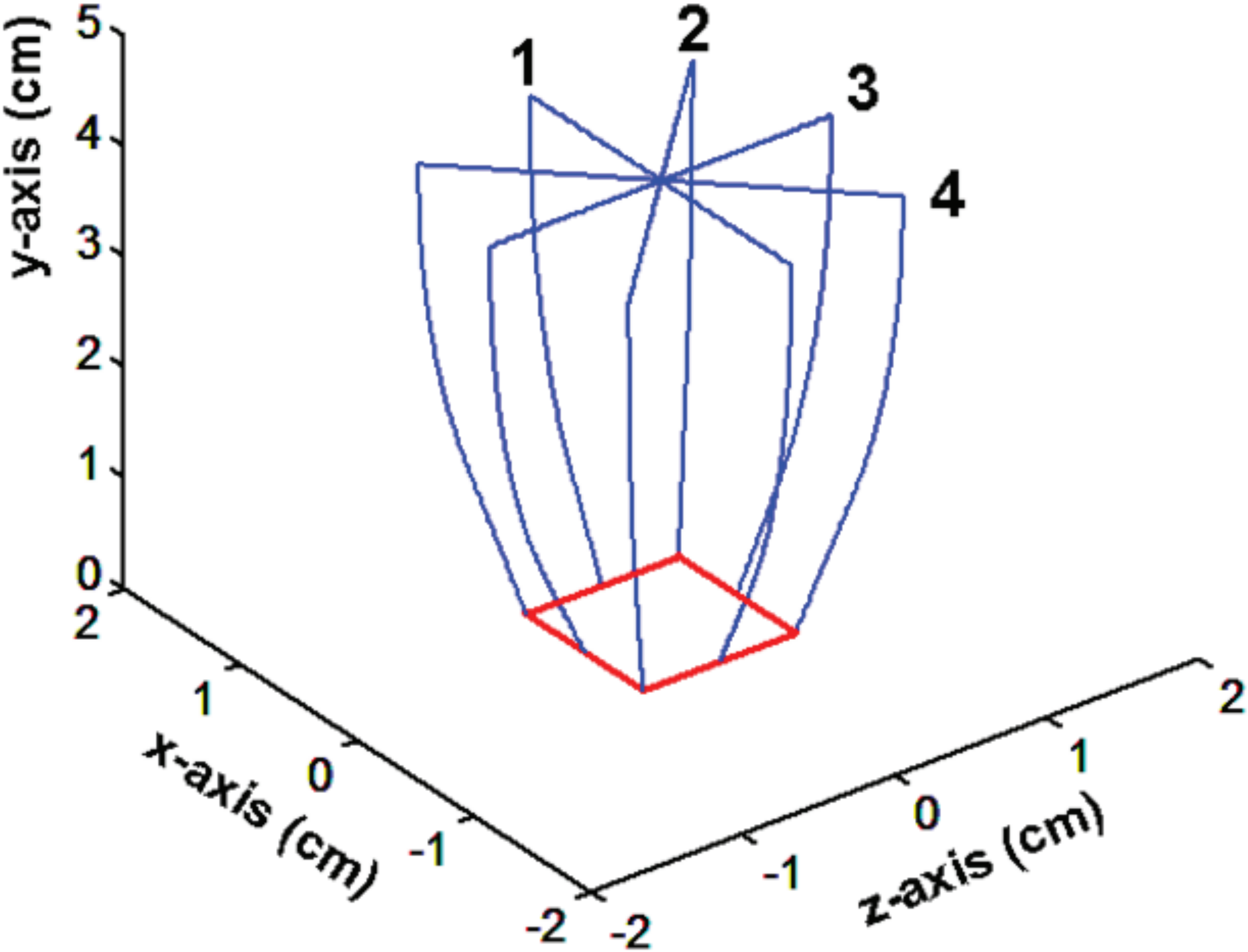

Figure 5

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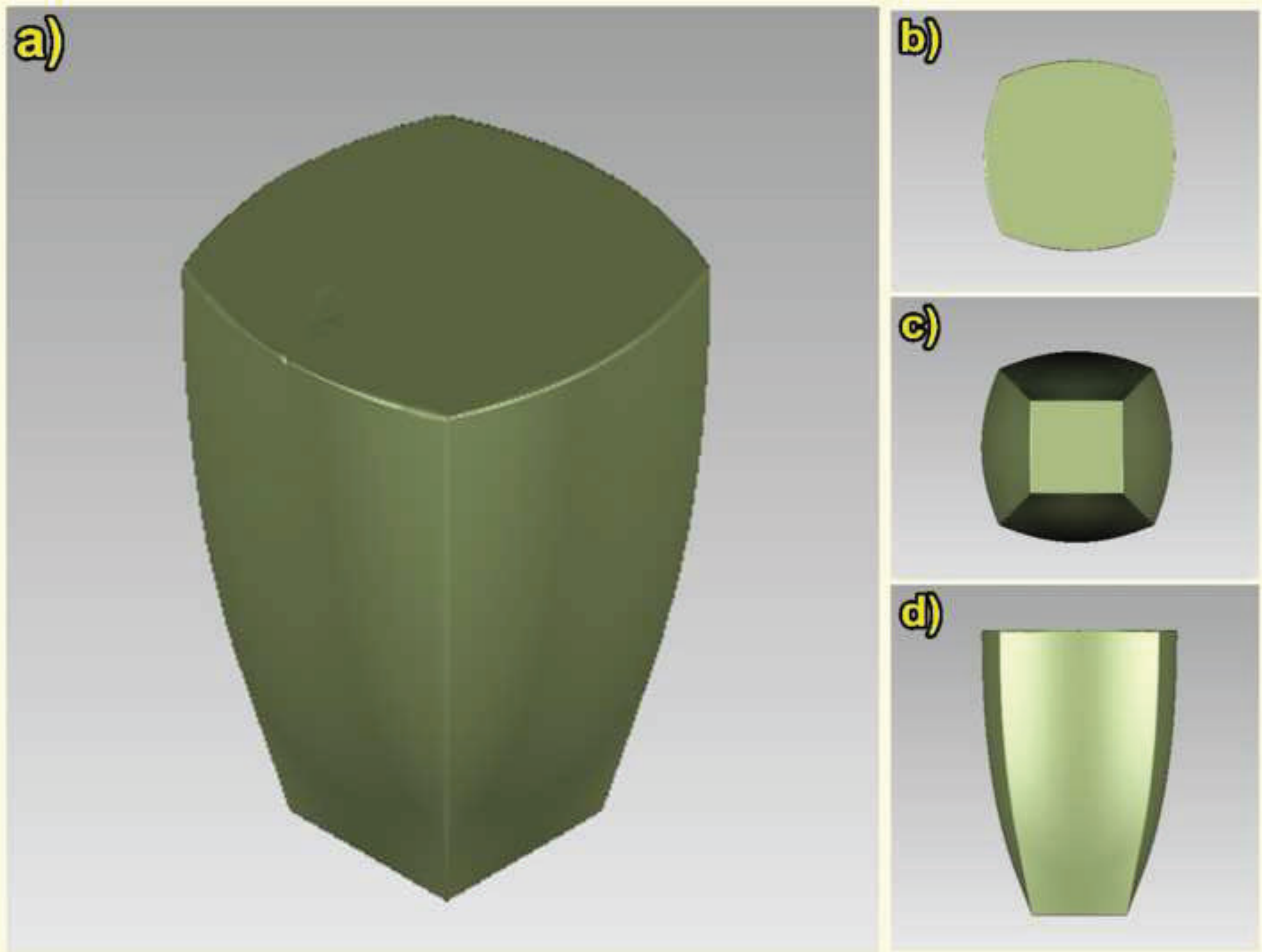

Figure 6
Click here to download high resolution image

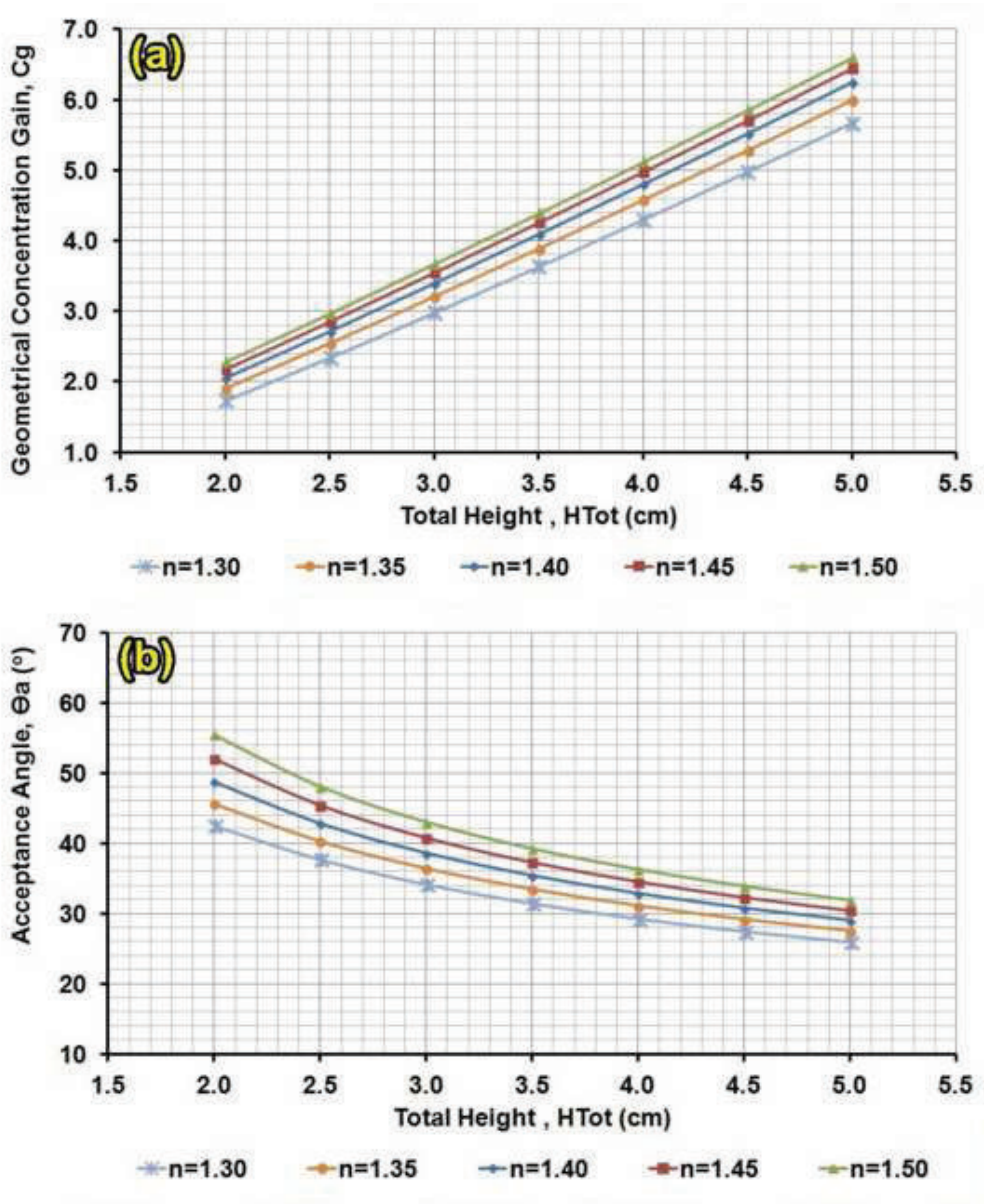

Figure 7

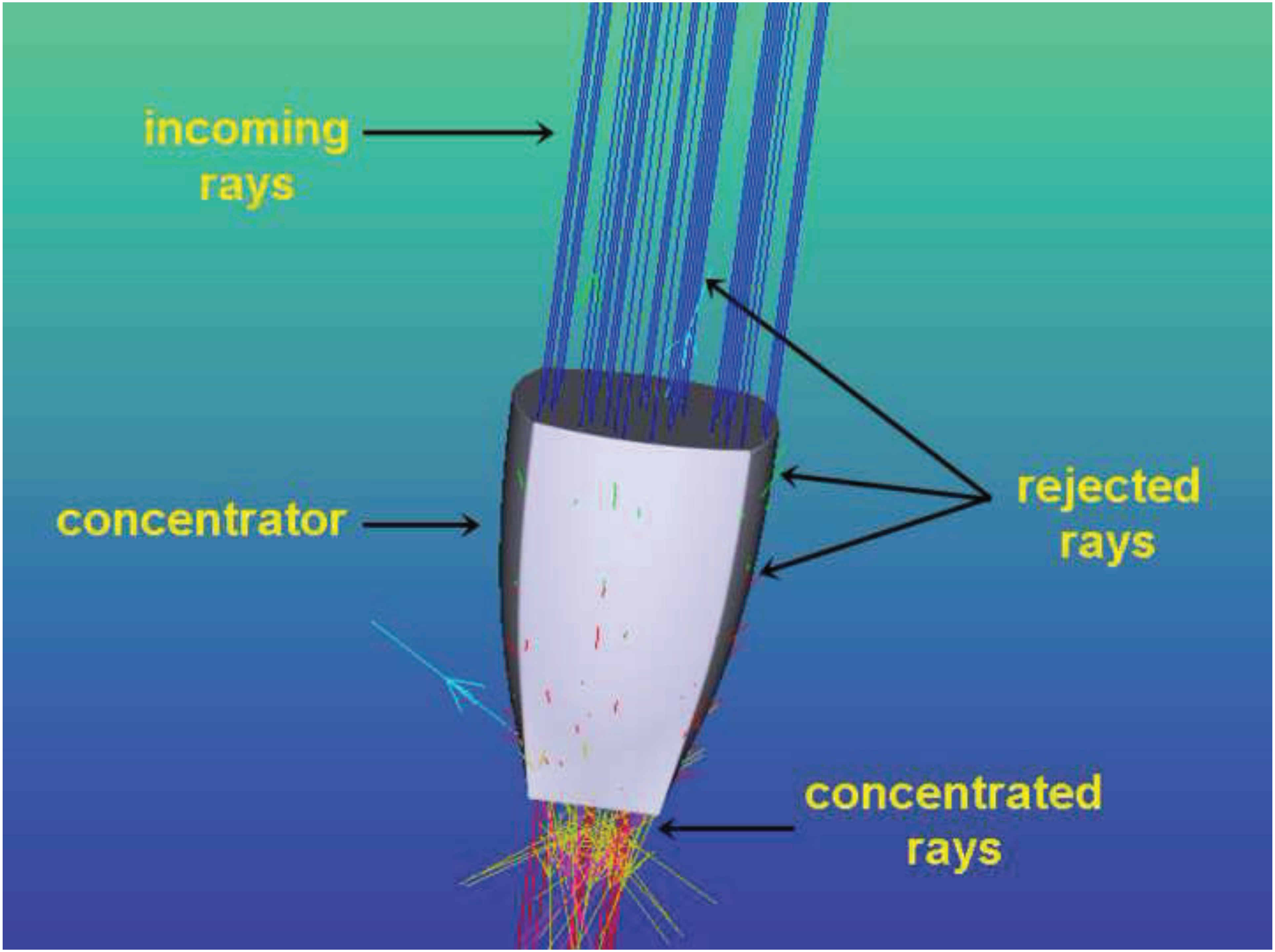
incoming
rays
concentrator
rejected
rays
concentrated
rays

Figure 8

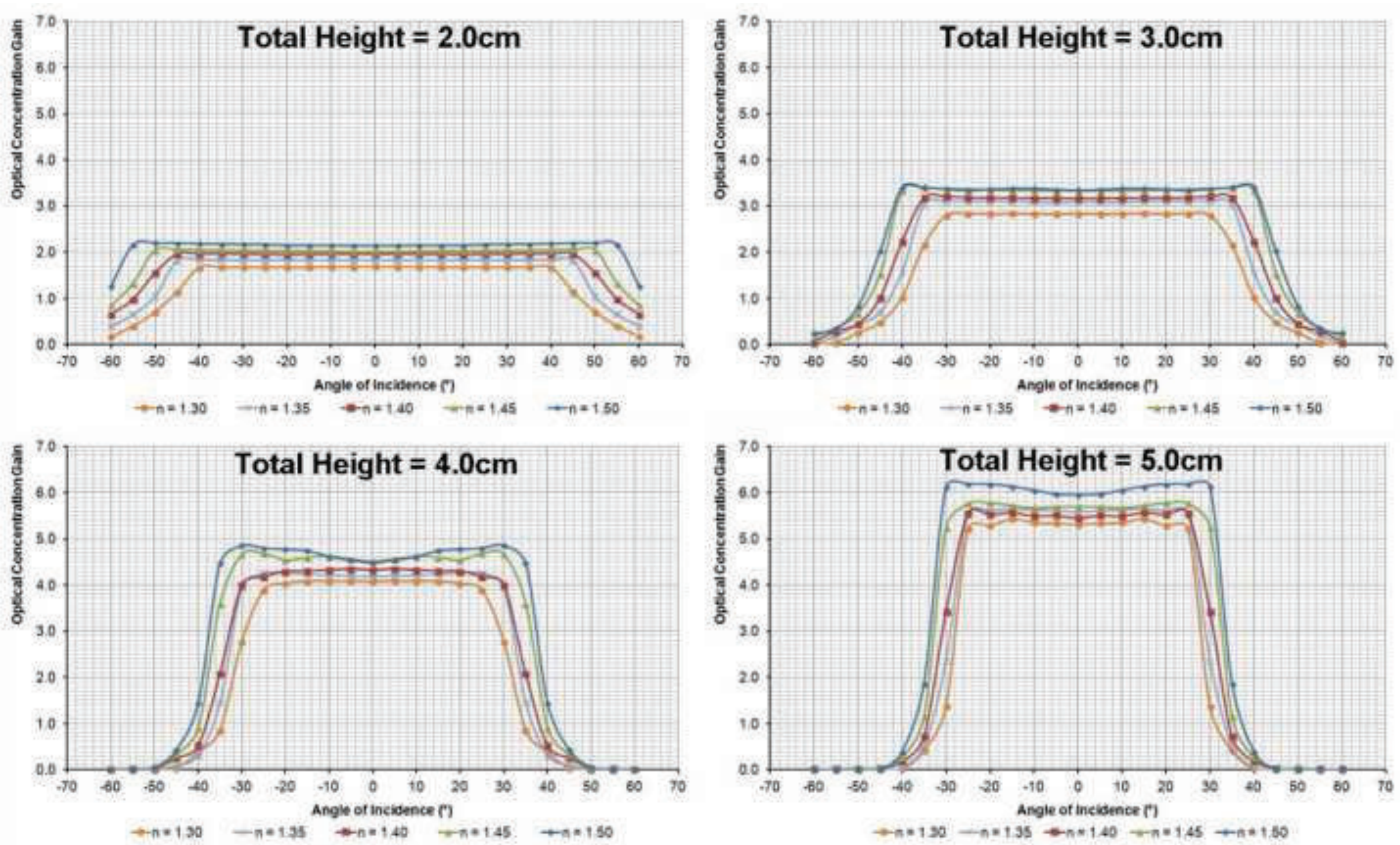
Total Height = 2.0cm
Total Height = 3.0cm
Total Height = 4.0cm
Total Height = 5.0cm
Optical Concentration Gain
Angle of Incidence (°)
n = 1.30
n = 1.35
n = 1.40
n = 1.45
n = 1.50

Figure 9

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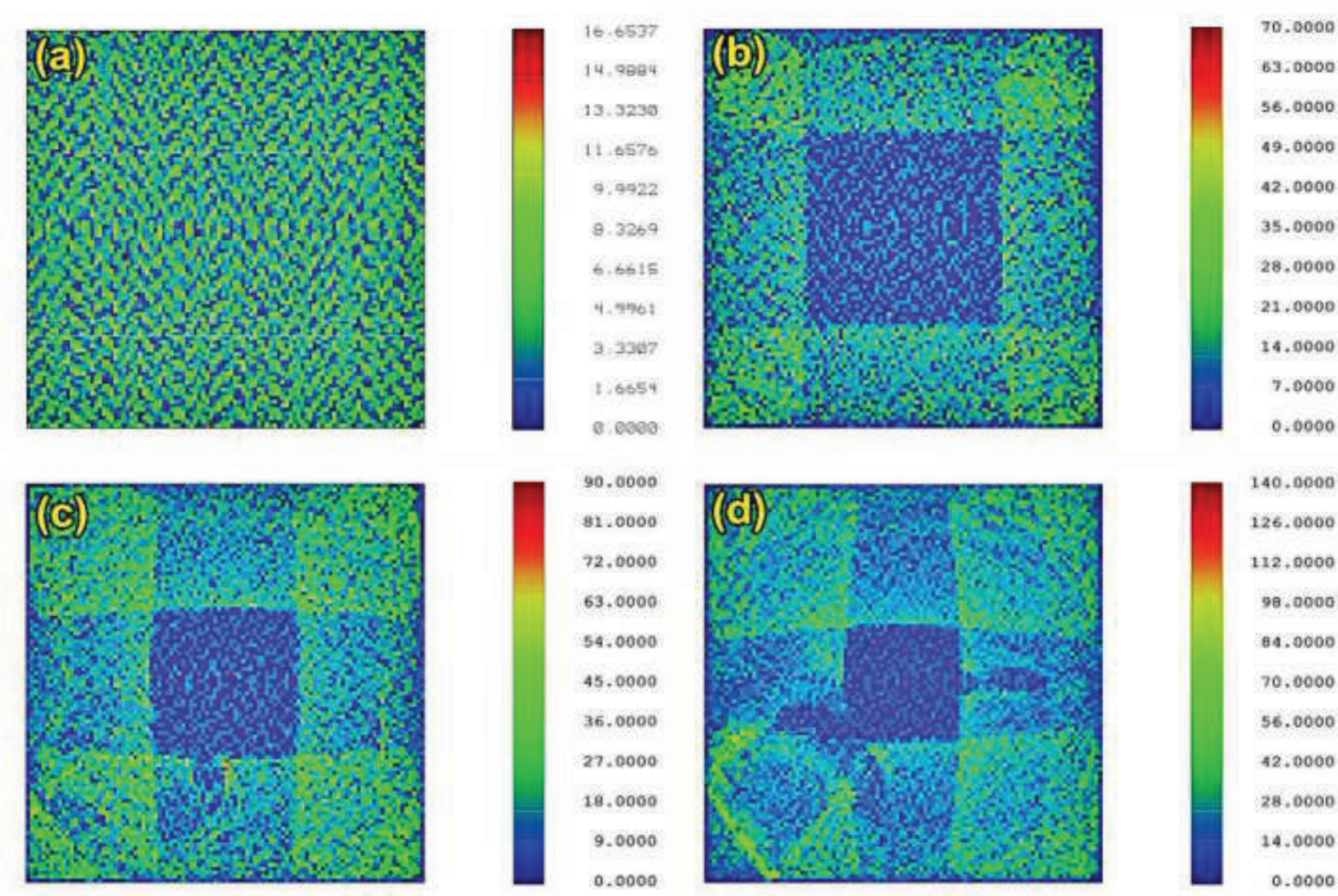

Figure 10

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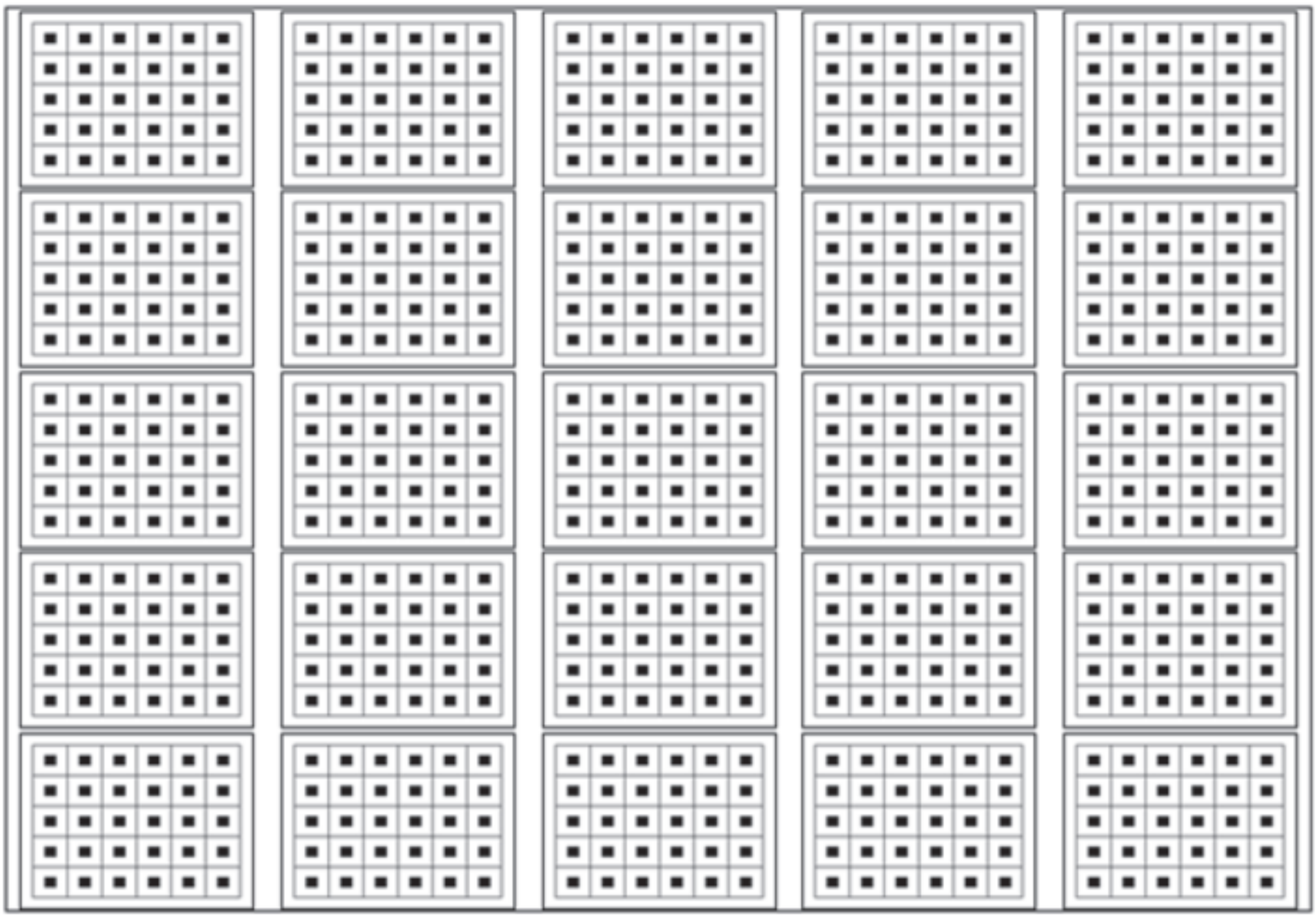

Figure 11

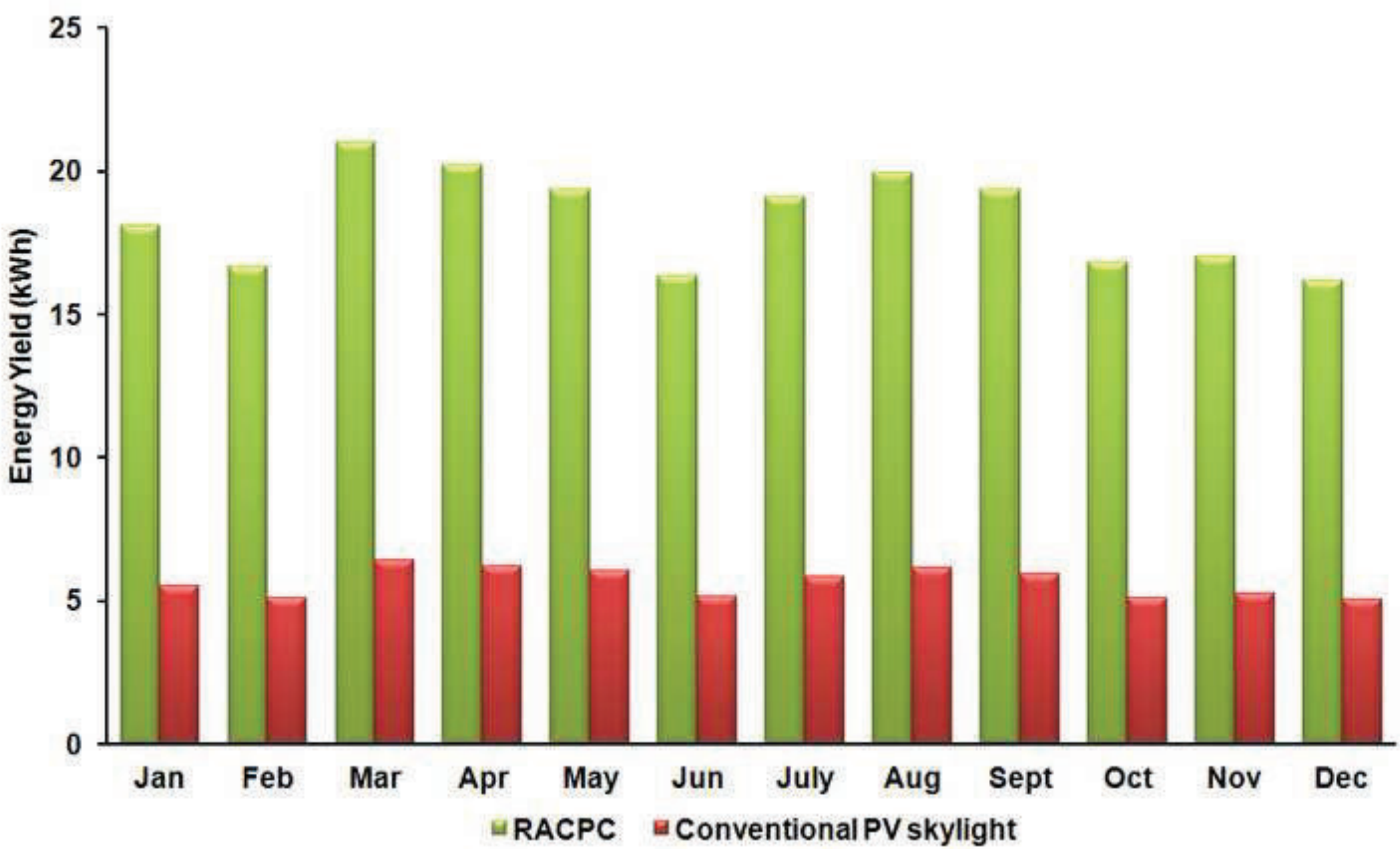
Energy Yield (kWh)
25
20
15
10
5
0
Jan
Feb
Mar
Apr
May
Jun
July
Aug
Sept
Oct
Nov
Dec
RACPC
Conventional PV skylight

Table 1

Table 1: Summary of various CPC designs that have been studied.

Authors	Type of CPC	Input parameters	Findings
Ronnelid et al. [36]	2D extrusion of a symmetrical reflective CPC.	A geometrical concentration gain of 1.53, an exit aperture width of 14.4 cm, a total height of 12 cm and a half-acceptance angle of 35º.	Increased the annual energy output by 2.6% when compared with the non-concentrating system. This concentrator has a CAP of 0.88.
Pei et al. [37]	2D extrusion of a symmetrical dielectric CPC	A geometrical concentration gain of 2.41, an exit aperture width of 1 cm, total height of 2.7 cm and a half-acceptance angle of 36.8º.	Increased the electrical power from 25.86 mW to 44.80 mW when compared with non-concentrating PV. It is calculated that the CAP of the concentrator is 1.44.
Cooper et al. [38]	Reflective 3D rotationally symmetric CPC	Half-acceptance angle of 30º.	The transmission-angle curve of the reflective design produced an almost ideal step-like behavior within its designed acceptance angle
Goodman et al. [39]	Dielectric 3D rotationally symmetric CPC	A geometrical concentration gain of 6.1, an index of refraction of 1.5 and half-acceptance angle of 10°.	The cell coupled with this CPC design produced a 5.7 more short circuit current when compared with a bare solar cell. This concentrator has a CAP of 0.43.
Mallick et al. [40]	Reflective ACPC.	A geometrical concentration gain of 2.	Increased the maximum electrical output power by 62% when compared with a non-concentrating system, achieving a maximum optical efficiency of 85.85%
Sarmah et al. [41]	Dielectric ACPC	A geometrical concentration gain of 2.8.	Achieved a maximum optical efficiency of 80.5% and increased the electrical power ratio to 2.27 when compared with a system without a concentrator.
Mammo et al. [42]	Reflective 3D CCPC.	A geometrical concentration gain of 3.61, a half-acceptance angle of 30º, a total height of 1.616 cm and a square 1 cm by 1 cm exit aperture.	Generated a maximum power concentration of 3 when compared to similar type of non-concentrating module. The CAP of the concentrator is 0.95.
Baig et al. [43]	Dielectric 3D CCPC.	A geometrical concentration gain of 3.61, a total height of 1.616 cm and a square 1 cm by 1 cm exit aperture.	Achieved a maximum optical efficiency of 73.4%, a half-acceptance angle of 35º and produced a maximum power ratio of 2.67 when compared with the non-concentrating design. The CAP of the concentrator is 1.09.

Table 2

Table 2: Comparison of acceptance angle values generated from the ZEMAX® simulation and from MATLAB® simulation.

Total Height, *HTot* (cm)	Geometrical concentration gain, C_g	Concentration-Acceptance Product, *CAP*	Index of refraction, *n*	Maximum optical efficiency, $C_{opt\text{-}eff}$	Half-acceptance angle obtained from ZEMAX®, Θ_a (º)	Half-acceptance angle obtained from MATLAB®, Θ_a (º)	Percentage of change (%)
2.00	1.73	0.88	1.30	0.98	42.00	42.50	1.17
	1.90	0.99	1.35	0.96	46.00	45.63	-0.81
	2.05	1.06	1.40	0.96	48.00	48.79	1.62
	2.17	1.16	1.45	0.95	52.00	52.02	0.05
	2.28	1.25	1.50	0.96	56.00	55.39	-1.10
3.00	2.98	0.94	1.30	0.95	33.00	34.13	3.32
	3.21	1.05	1.35	0.97	36.00	36.40	1.10
	3.39	1.11	1.40	0.94	37.00	38.61	4.17
	3.54	1.24	1.45	0.95	41.00	40.79	-0.52
	3.67	1.28	1.50	0.93	42.00	42.96	2.23
4.00	4.30	0.94	1.30	0.95	27.00	29.23	7.62
	4.58	1.07	1.35	0.93	30.00	31.06	3.42
	4.80	1.13	1.40	0.90	31.00	32.83	5.57
	4.97	1.21	1.45	0.93	33.00	34.55	4.47
	5.11	1.30	1.50	0.95	35.00	36.23	3.39
5.00	5.67	1.04	1.30	0.96	26.00	25.92	-0.32
	5.99	1.07	1.35	0.94	26.00	27.49	5.41
	6.25	1.13	1.40	0.89	27.00	28.99	6.85
	6.44	1.27	1.45	0.90	30.00	30.43	1.42
	6.59	1.32	1.50	0.94	31.00	31.84	2.63