

## Characteristics Review of Optical Concentrators

Sabah Auda Abdul Ameer\* and Haroun A.K Shahad

Mechanical Engineering Department, University of Babylon, Babel-Iraq

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### Abstract

*This study includes a comprehensive review of researchers related to optical concentrators. Parameters which affect their concentration levels are likewise talked about. Their properties, designations and mathematical formula are mentioned. Many designs have been set forth for concentrating collectors. Concentrators can be classified the reflectors or refractors, cylindrical or surfaces of revolution, and continuous or segmented. Receivers can be convex, flat, or concave and can be covered or uncovered. Many modes of tracking are possible. Concentration ratio (the ratio of the collector aperture area of absorber area, which is approximately the factors by which radiation flux on the energy-absorbing surface is increased) can vary over several orders of magnitude. With this wide range of inventions, it is difficult to develop general analyses applicable to all concentrators. Thus concentrators are treated in two groups: Non-imaging collectors with low concentration ratio and linear imaging collectors with intermediate concentration ratio. Some basic considerations of three-dimensional concentrators that can operate at the high end of the concentration ratio scale are also noted.*

**Keywords:** Optical concentrator; non-imaging; CPC

### 1. Introduction: Collector configurations

Many concentrator types are possible for increasing the flux of the radiation on the receivers. In general, concentrators with receivers much smaller than the aperture (the plane opening of the concentrator through which the solar radiation passes) are effective only on beam (direct) radiation. It is also plain that the angle of incidence of the beam radiation on the concentrator is important and that sun tracking will be postulated for these collectors. A variety of orienting mechanisms have been designed to move focusing collectors so that the incident beam radiation will always be reflected to the receiver. Linear (cylindrical) optical systems focus beam radiation onto the receiver if the sun is in the central plane of the concentrator (the plane, including the focal axis and the vortex line of the reflector). These collectors can be rotated about a single axis of rotation, which may be north-south, east-west, or inclined and parallel to the earth's axis (in which case the rate of rotation is  $15^\circ/\text{h}$ ). There are significant differences in both quantity of incident beam radiation, its time dependence and the image quality obtained with these three modes of orientation Duffie J. A. And Beckman, W. A. Reflectors that are surfacing of revolution (circular concentrators) are optically oriented so that their axis is in line with the sun and thus must be able to move about two axes.

These may be horizontal and vertical, or one axis of motion may be inclined so that it is parallel to the earth's axis of rotation (i.e. A polar axis) and the other perpendicular to it. Orientation systems can provide continuous or nearly continuous adjustments, with movement of the collector to compensate for the changing position of the sun. For some low concentration linear collectors it is possible to adjust their position intermittently, with weekly, monthly, or seasonal changes possible for some designs. Continuous orientation systems may be based on manual or mechanized operation.

Manual systems depend on the observations of operators and their skill at making the necessary corrections. This may be adequate for some purposes if concentration ratios are not too high and if labor costs are not prohibitive; they have been suggested for use in areas of very low labor cost. Mechanized orienting systems can be sun seeking systems or programmed systems. Sun-seeking systems use detectors to determine system misalignment and through controls make the necessary corrections to realign the assembly. Programmed systems, on the other hand, cause the collector to be moved in a predetermined manner (e.g.  $15^\circ/\text{hr}$  about the polar axis) and may need only occasional checking to assure alignment. It may also be advantageous to use a combination of these tracking methods, for example, by superimposing small corrections by a sun-seeking mechanism on a programmed rough positioning system. Any

\*Corresponding author: Sabah Auda Abdul Ameer

mechanized system must have the capability of adjusting the position of the collector from end-of-day position to that for operation early the next day, adjusting for intermittent clouds, and adjusting to a safe position where it can best withstand very high winds without damage Duffie J. A. And Beckman, W. A.

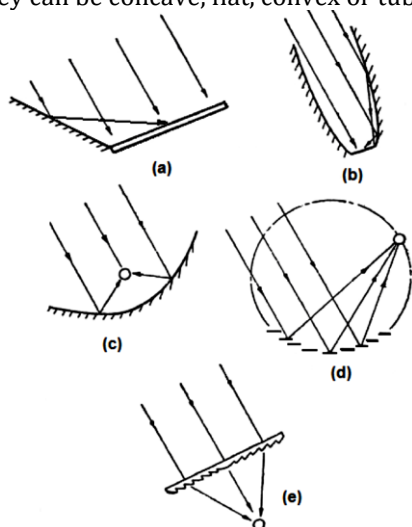
1.1 Classification of optical concentrators

There are varieties of different concentrator designs. They are classified into two major optical categories: (I) Imaging optics concentrators. (II) Non-imaging optic concentrators.

In the imaging optic concentrators, it is concerned with the image formed by the optical concentrator on the receiver, so that the receiver must be small enough to attain some homogeneity in the distribution of the formed image (focus). Thus, the imaging optic concentrators have their advantage that they have a high value of concentration. On the other hand, in the non-imaging optics, it is not concerned with forming an image, and thus the receiver may be large with the homogeneity of the radiation on the receiver, but its concentration is smaller than that of imaging optic concentrators.

1.2 Types of optical concentrators

Many types of optical concentrators are possible for increasing the flux of radiation on receivers. For the imaging type of concentrators, they can be cylindrical to focus on a line or circular to focus on a point, while for the non-imaging one; they can be in the trough like shape for the long absorber or in conical shape for circular absorber. Receivers can also take different forms; they can be concave, flat, convex or tubular.



(a) Flat plate collector with plane reflectors (FPC)  
 (b) Compound parabolic collector (CPC)  
 (c) Cylindrical parabolic collector (CPT)  
 (d) Collector with fixed circular concentrator and moving receiver  
 (e) Fresnel lens concentrating collector (FL)

Fig. 1 Types of the concentration collectors (Sukhatme S. P.)

Some of them are mentioned here:

- 1) Flat Plate Collector (FPC).
- 2) Parabolic Trough Concentrator (PTC).
- 3) V-Trough Concentrator (VTC).
- 4) Compound Parabolic Concentrator (CPC).
- 5) Central Receiver Collector.
- 6) Fresnel Lens Concentrator.
- 7) Conical Concentrator.
- 8) Paraboloidal Concentrator.
- 9) Compound Elliptical Concentrator (CEC).
- 10) Hyperboloid Concentrator (Trumpet Concentrator).
- 11) Spherical Concentrator.
- 12) Pyramidal Concentrator.

2. Definitions related to concentrators

There are five related terms: aperture, concentration ratio, acceptance angle, intercept factor, and incidence angle modifier. The first three terms are common in both of the two main categories of concentrators mentioned above (imaging and non-imaging optical concentrators), while the last two are only special for the imaging optical concentrators. Here the terms related to non-imaging concentrators only are defined.

The aperture (W):

It is the plane opening of the concentrator through which the solar radiation passes. For a 2-D cylindrical or linear concentrator, it is characterized by the width, while for a 3-D, formed by surface of revolution; it is characterized by the diameter of the opening.

The concentration ratio (C):

There are two natural definitions of concentration ratio that have been in use; to avoid confusion a subscript should be added whenever the context does not clearly specify which definition is meant. The first definition is strictly geometrical and named Geometric Concentration or Area Concentration, while the second one is in terms of the ratio of the measured intensity and named Intensity Concentration or Flux Concentration.

The area concentration (C<sub>area</sub>):

It is the ratio of the effective area of the aperture to the surface area of the absorber.

$$C_{area} = A_a / A_r \tag{1}$$

Where, A<sub>a</sub> is the area of the aperture and A<sub>r</sub> is the area of the receiver (the absorber) of the concentrator.

The flux concentration (C<sub>flux</sub>):

It is the ratio of the intensity of the aperture to that at the absorber.

$$C_{flux} = I_a / I_r \tag{2}$$

Where,  $I_a$  is the value of flux at the aperture and  $I_r$  is the value of the flux of the receiver (the absorber) of the concentrator. The values of the concentration ratio vary from unity (which is the limiting case of a flat plate collector) to a few thousand for a paraboloidal dish.

The acceptance angle ( $2\theta_c$ ):

It is the angle over which beam radiation may deviate from the normal to the aperture plane and yet reach the absorber without moving all or part of the collector. The geometrical optics and the second law of thermodynamics require that the maximum possible concentration for a given collector acceptance half angle  $\theta$  is:

$$C_{ideal,2D} = 1 / \sin^2 \theta \tag{3}$$

For two-dimensional (trough like) concentrators, and

$$C_{ideal,3D} = 1 / \sin^2 \theta \tag{4}$$

For three-dimensional ones (cones, dishes, pyramids). Collectors with large acceptance angles require only occasional adjustments, while collectors with small acceptance angles have to be adjusted continuously.

### 3. Applications of concentrators

Concentrating collectors are of various types and can be classified in many ways. They may be of the reflecting type utilizing mirrors or of the refracting type utilizing Fresnel lenses. The reflecting surfaces used may be parabolic, spherical or flat.

**Table 1** Summary of applications of different concentrator types

Tracking mode	Examples	Approx. Range of CR	Approx. maximum operating temperature
None (Tilt fixed)	CPC	1.5 to 2.0	Up to 100 <sup>o</sup> C no vacuum Up to 150 <sup>o</sup> C vacuum
None (Two tilt adjustment per year)	V-trough	1.5 to 2.0	Up to 150 <sup>o</sup> C vacuum
	CPC	3.0	Up to 180 <sup>o</sup> C vacuum
None (Tilt adjustment seasonal to daily)	V-trough	2 to 3	Up to 180 <sup>o</sup> C vacuum
	CPC	3 to 10	100 <sup>o</sup> to 150 <sup>o</sup> C no vacuum 150 <sup>o</sup> to 250 <sup>o</sup> C vacuum
One axis tracking	Fresnel lens	6 to 30	200 <sup>o</sup> to 300 <sup>o</sup> C (with second stage concentrator, vacuum and selective absorber upto 400 <sup>o</sup> to 500 <sup>o</sup> C)
	Parabolic trough		
	Fresnel mirror moving receiver	15 to 50	
Two axis tracking	Fixed spherical reflector plus tracking receiver	50 to 150	300 <sup>o</sup> to 500 <sup>o</sup> C
	Fresnel lens	100 to 1000	400 <sup>o</sup> to 1000 <sup>o</sup> C
	Parabolic dish power tower	500 to 3000	500 <sup>o</sup> to 2000 <sup>o</sup> C

They may be continuous or segmented. Classification is also possible from the point of view of the formation of the image, the concentrator being either imaging or non-imaging. Further, the imaging concentrator may focus on a line or at a point Sukhatme S. P. The concentration ratio is also used as a measure for classifying concentrating collectors. Since this ratio approximately determines the operating temperature,

this method of classification is equivalent to classifying the collector by its operating temperature range. A final possibility is to describe concentrating collectors by the type of tracking adopted. Depending on the acceptance angle, the tracking may be intermittent (one adjustment daily or every few days) or continuous. Further, the tracking may be required about one axis or two axes. Table (1) represents some applications of different concentrator types.

### 4. Compound parabolic concentrator (CPC)

The basic concept of the Compound Parabolic Concentrator is shown in Fig.1 (b). This concentrator belongs to the non-imaging category of concentrators, in which there is no dealing with image forming. It has a large acceptance angle and requires only intermittent tracking. The usefulness of the geometry of the CPC for solar energy collection was noted by R. Winston and it has been the subject of considerable development in the last few years.

#### 4.1 Geometry of CPC

The geometry of the two-dimensional CPC is shown in Fig. 2. The concentrator consists of two segments AB and DC which are parts of two parabolas 1 and 2. AD is the aperture of width W and BC the absorber surface of width b. The axes of the two parabolas are oriented to each other at an angle that the point C is the focus of parabola 1 and point B is the focus of parabola 2. Tangents drawn to the parabolas at points A and D are parallel to the axis of the CPC. Fig.2 Geometry of a compound parabolic concentrating collector. The acceptance angle of the CPC is the angle AED ( $2\theta_c$ ) made by the lines obtained by joining each focus to the opposite aperture edge. The CPC, first proposed by Winston and Hinterberger, has the capability of reflecting all the insolation to the absorber over a relatively wide range of angles. Abdul-Jabbar and Salman concluded through a series of experiments in the middle-east that the CPC solar collectors with the double axis tracking system can get up to 75% more insolation. Kim et al used both numerical and experimental methods to achieve the thermal efficiency of a CPC solar collector with single-axis tracking system of about 14.9% higher than a stationary CPC solar collector. Weinstock and Appelbaum compared the energy outputs of stationary flat plate solar collectors and flat plate solar collectors with various tracking systems. Small concentration ratio truncated CPC solar collectors without a tracking system are widely used in practice. Since the higher part of the parabola will prevent the radiation during some specific times, it will make the overall performance of the CPC solar collectors poor. Truncated CPC solar collectors are usually applied because a large portion of the reflector area can be eliminated in order to save the cost without seriously reducing the concentration. Many researchers discussed and recommended that the acceptance angle

of CPC solar collectors should lie between 25 deg. and 55 deg. depending on the environment. Some researchers designed different asymmetric parabolic reflectors in order to attract more insolation. Mills and Giutronich concluded, based on a comparative study of symmetrical and asymmetrical parabolic concentrators, that asymmetrical design could collect higher and more stable energy. Tripanagnostopoulos et al. compared the performance of three small CPC units and one large CPC unit, with the aperture area of the larger unit equal to three times more than that of the smaller units through experiments and confirmed that the three smaller units performed better than the large unit. Mallick et al. designed, constructed, and experimentally tested a prototype asymmetric CPC solar collector. For the same receiving area, the power output of the CPC collector was found to be 1.62 times more than that of a flat plate photovoltaic panel. Other researchers focused on the design of different types of receivers. In general, receivers can be designed as a flat plate (as shown in Fig.2), V-type or cylindrical type. Other practical designs with multi channels and bifacial absorbers have also been used. Since a CPC solar collector has the merits of flat plate solar collector and concentrating collector, it is an excellent substitute for a flat plate solar collector. The CPC solar collectors can offer superior yearly energy delivery at comparable cost and reach considerably higher temperatures than most flat plate collectors in thermal applications. Similar to flat plate solar collectors, the CPC solar collectors are also used for increasing the intensity of irradiation in order to improve the performance of photovoltaic solar panels.

For large area solar panel applications, a multi row CPC solar collector system needs to be designed and optimized. As shown in Fig. 2 a, increasing the number of solar collector rows and height of the collector will definitely increase the total collector area; however, it also increases the shading area which will reduce the radiation energy received from the sun. Weinstock and Appelbaum, Hu and Rao and Rao and Hu considered different types of optimum designs for large area multi row flat plate solar collector systems with shading effects. However, the shading effect has not been considered in a large area multi row CPC panel design problems until now. Rao and Hu are to incorporate the shading effect in a large area multi row optimum design of CPC collectors for heating application (such as in a multistory building). Three objectives, including the maximization of the annual average incident solar energy, maximization of the incident solar energy for the lowest month, and minimization of cost, are considered separately and simultaneously. F. Bloisi et. al study four type of (CPC) collector. The four type of CPC collector are different in shape of absorber. The researchers study the effect of acceptance angle, height and width to the design of collector. Zaki et. al. reported that thermal losses from the CPC collector, due to a smaller absorber surface area, were significantly reduced resulting in an increased thermal efficiency. Norton et. al. in a study investigated a

possible rural application studied for the Compound Parabolic Concentrator (CPC) suggested the incorporation of a basin type still with an inverted absorber line-axis asymmetric CPC. The inverted absorber configuration can achieve higher temperatures by minimizing thermal losses by convection suppression. Lixi Zhang et. al designed a new solar-heated generation system with capacity of 10kW. The CPC solar energy collector array is used as the main heat source (with concentration ratio equal 5), and the gas boiler as the assistant heat source. The shape of the CPC solar collector is designed, and the thermal efficiency is analyzed, and the collector array is ranged suitably. Finally, the economical benefit of the system is discussed. Luisa I. and Feliciano-Cruz reported the design of a simulation model for the analysis and performance evaluation of a Solar Thermal Power Plant in Puerto Rico and suggested the use of the Compound Parabolic Concentrator (CPC) as the solar collector of choice. The solar array would consist of 80 series collectors (1.52 m wide, 12 m long with a height of 1.97 m and a reflector area of 49.6 m<sup>2</sup>).

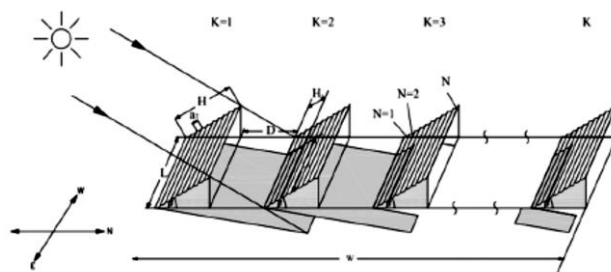


Fig. 2 a Multirow compound parabolic collector in a given area

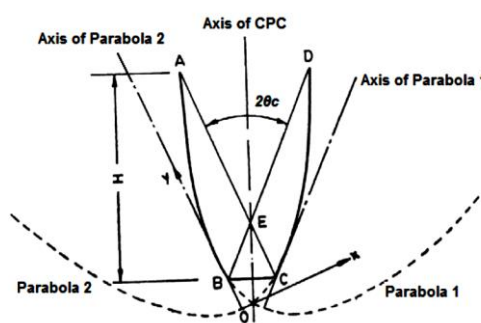


Fig. 2 b Geometry of a compound parabolic concentrating collector

The concentration ratio is given by:

$$C = W / b = 1 / \sin\theta_c \tag{5}$$

This concentration ratio is the maximum possible for the acceptance angle  $2\theta$ . Using the x-y coordinate system shown in Fig.2, with origin O at the vertex of parabola 2, it is easy to show that the equation for parabola 2 is:

$$y = \frac{x^2}{2b(1+\sin\theta_c)} \tag{6}$$

Where, the focal length is given by:

$$\tau = \rho^n \tag{16}$$

$$OB = \frac{b}{2}(1 + \sin\theta c) \tag{7}$$

Where,  $\rho$  is the reflectivity value for single reflection.

The coordinates of the end points of the segment CD are as follows:

Point C:  
 $X = b \cos\theta c$  (8)

$$Y = \frac{b}{2}(1 - \sin\theta c) \tag{9}$$

Point D:  
 $X = (b + W) \cos\theta c$  (10)

$$Y = \frac{b}{2}(1 - \sin\theta c) \left(1 + \frac{1}{\sin\theta c}\right) \tag{11}$$

The height to aperture ratio of the concentrator is given by:

$$\frac{H}{W} = \frac{1}{2} \left(1 + \frac{1}{\sin\theta c}\right) \cos\theta c = \frac{1}{2} (1 + C) \left(1 - \frac{1}{C^2}\right)^{1/2} \tag{12}$$

The surface area of the concentrator is obtained by integrating along the parabolic arc. Rabl has shown that the ratio of the surface area of the concentrator to the area of the aperture is calculated using the following reflector arc length (L) expression:

$$L = b(1 + \sin\theta c) \left[ \frac{\cos\theta c}{\sin^2\theta c} + \ln \left\{ \frac{(1 + \sin\theta c)(1 + \cos\theta c)}{\sin\theta c [\cos\theta c + (2 + 2\sin\theta c)^{0.5}]} \right\} - \frac{\sqrt{2}\cos\theta c}{(1 + \sin\theta c)^{3/2}} \right] \tag{13}$$

For values of concentration ratio greater than 3, it can be shown that the following simple expression (which predicts values to accuracy better than 5%) may be used in place of Eq. (13)

$$\frac{A_m}{WL_a} = 1 + C \tag{14}$$

Here  $L_a$  is the axial length of the CPC trough and  $A_m = L \times La$ .

Rabl has also shown that the average number of reflections  $n$  undergone by all radiation falling within the acceptance angle before reaching the absorber surface is given by the expression:

$$n = \frac{1}{2\sin\theta c} \left( \frac{A_m}{WL_a} \right) - \frac{(1 - \sin\theta c)(1 + 2\sin\theta c)}{2\sin^2\theta c} \tag{15}$$

Where, the value of  $(A_m/WL_a)$  is to be calculated from Eq. (13) or (14). Thus, the effective transmissivity  $\tau$  (reflectivity) of the concentrator surface is given by:

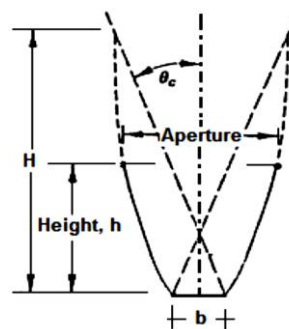


Fig. 3 A CPC truncated so its height-aperture ratio is about one-half of the full CPC

It is found that compared to a cylindrical parabolic collector, a CPC is very deep and requires a large concentrator area for a given aperture. Fortunately, however, it has been shown that a large portion of the top of a CPC can be removed with negligible loss in performance. Thus, in practice, a CPC is generally truncated (reduced in height) by about 50% in order to reduce its cost. A truncated CPC is shown in Fig. 3. The dashed plot in Fig 4 shows the spread of the image for the truncated concentrator. Limited truncation affects the acceptance angle very little, but it does change the height-to- aperture ratio, the concentration ratio and the average number of reflections undergone by radiation before it reaches the absorber surface. The effects of truncation are shown for otherwise ideal CPCs in Fig.5 to Fig.7. Fig. 5 shows the height-to-aperture ratio and Fig.6 shows the ratio of reflector area to aperture area. Fig.7 shows the average number of reflections undergone by radiation entering the aperture before it reaches the absorber. If the truncation is such that the average number of reflections is below the  $(N)_{min}$  curve, that average number is at least  $(1 - 1/C)$ . Rabl A, gave equations for all of these quantities.

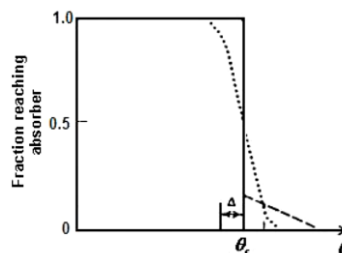
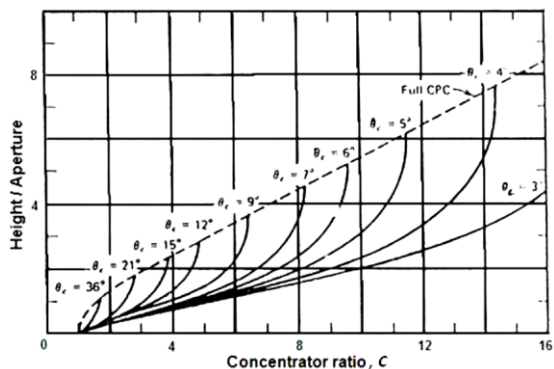
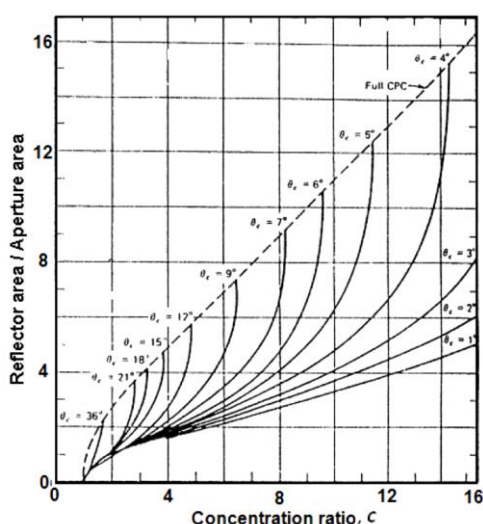


Fig. 4 Fraction of radiation incident on the aperture of a CPC at angle  $\theta c$  which reaches the absorber surface if  $\rho = 1$ .  $\theta c$  is the acceptance half-angle and is an angular surface error. Full CPC with no surface errors, (continuous line); truncated CPC with no surface errors, (dashed line), full CPC with surface errors, (dotted line). Rabl A.

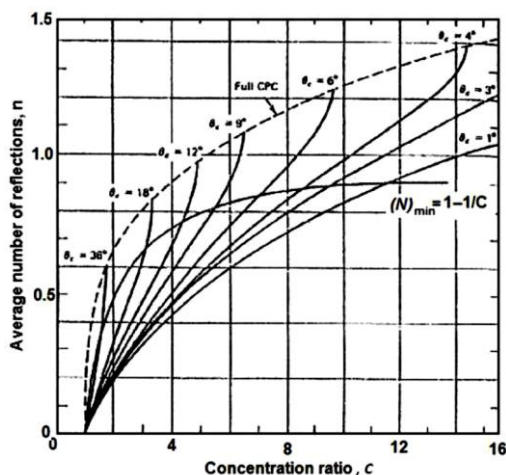




**Fig.5** Ratio of height to aperture for full and truncated CPCs as a function of  $C$  and  $\theta_c$ . Rabl A



**Fig.6** Ratio of reflector area to aperture area for full and truncated CPCs



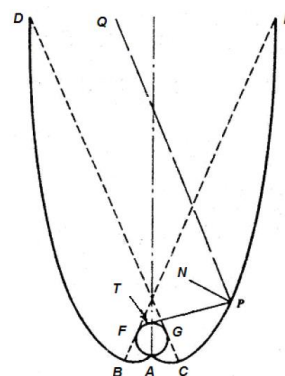
**Fig.7** The average number of reflections undergone by radiation within the acceptance angle reaching the absorber surface of full and truncated CPCs

The use of these plots can be illustrated as follows. An ideal full CPC has an acceptance half angle  $\theta$  of 12°. From Fig.5 the height-to-aperture ratio is 2.8 and the concentration ratio is 4.8. From Fig.6 the area of

reflector required is 5.6 times the aperture. The average number of reflections undergone by radiation before reaching the absorber surface is 0.97 from Fig.7. If this CPC is truncated so that its height-to-aperture ratio is 1.4, from Fig.5 the concentration ratio will drop to 4.2. Then from Fig.6 the reflector area-aperture area ratio is 3.0 and from Fig.7 the average number of reflections will be at least  $(1 - 1/4.2) = 0.76$ . CPCs with flat receivers should have a gap between the receiver and the reflector to prevent the reflector from acting as a fin, conducting heat from the receiver. The gap results in a loss of reflector area and a corresponding loss in performance and should be kept small Duffie J. A. and Beckman W. A.

The preceding discussion has been based on flat receivers occupying the plane between the two foci as shown in Fig.2. Other receiver shapes can be used. CPC can be developed with aperture  $W$  which will concentrate incident radiation with incidence angles between  $\pm \theta$  onto any convex absorber with circumference  $W \sin \theta$ .

The method of generation of the shape of the CPC is illustrated by Fig.8, which shows a special case of interest, a cylindrical absorber. Parts AB and AC of the reflector are convolute of parts AF and AG of the absorber. The requirement for the rest of the reflector is that at any point P, the normal to the reflector NP must bisect the angle between the tangent to the absorber PT and the line QP, which is at an angle  $\theta$  to the axis of the CPC. This CPC is used with evacuated tubular receivers. They can be truncated in the same way as other CPCs. This method can be used to generate a reflector for any convex receiver shape. Thus a set of CPC-type concentrators (not necessarily parabolas) can be evolved that permit a range of choices of receiver shape. CPCs can be used in series; the receiver for a primary concentrator can be the aperture of a secondary concentrator. The concentrator need not be symmetrical.



**Fig.8** A CPC for a tubular receiver. Rabl A.

Tubular absorbers are often used with CPC reflectors Eames P. C. and Norton B.. The reflector shape leading to maximum absorption of radiation by cylindrical

absorbers is an involute as shown in Fig.9. McIntire W. R. and derived a mathematical analysis for using an absorber of a tubular shape in the CPC.

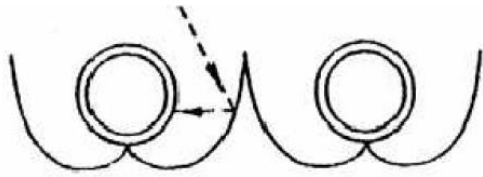


Fig.9 Involute reflector for use with cylindrical absorber

Shah P. K. and Patel L. N. developed and carried out the experimental investigation on an ideal compound parabolic concentrator with non-evacuated tubular absorber. It is unique in its design to give better thermal performance. There is a gap between the absorber envelope and the reflector of the CPC. As shown in Fig.10 the specific curvature of the reflector is designed and developed to reduce the bottom heat losses from the absorber.

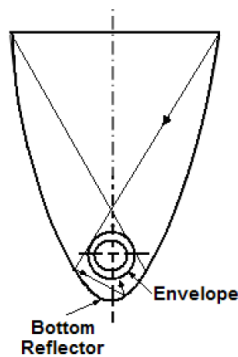


Fig.10 Ideal CPC with gap between envelope and reflector

Orientation and absorbed energy for CPC collectors

The advantages of CPCs are that they can function without continuous tracking and still achieve some concentration. However, they must be properly oriented to maximize the absorbed radiation when output from the collector is needed. It is necessary to calculate the absorbed radiation in order to determine the operation at any time. This is a step to finding the best orientation. A particularly critical question is whether or not the beam radiation will be absorbed. A logical orientation for such a collector is along a horizontal east-west axis, sloped toward the equator and adjustable about that axis. The CPC is arranged so that the pseudo incidence angle of beam radiation (the projection of the angle of incidence on the north-south vertical plane) lies within the limits  $\pm\theta$  during the times when output is needed from the collector. In practice, compromises are necessary for movement of the collector and the concentration ratio, with higher ratios associated with small acceptance angles and relatively frequent positioning. To estimate the

radiation absorbed by the receiver of a CPC, it is necessary to determine if the angle of incidence of the beam radiation is within the acceptance angle  $2\theta$ , and then estimate the contributions of the beam and diffuse radiation, plus the ground reflected radiation if it is within the acceptance angle Duffie J. A. and Beckman W.A. The absorbed radiation can be estimated as:

Solar irradiance at receiver: (Sr)

$$S_r = A_a \{ G_{b,cpc} \tau_{c,b} \tau_{cpc,b} \alpha_b + G_{d,cpc} \tau_{c,d} \tau_{cpc,d} \alpha_d + G_{g,cpc} \tau_{c,g} \tau_{cpc,g} \alpha_g \} \quad (17)$$

$$G_{b,cpc} = FG_{bn} \cos \theta \quad (18)$$

Where,

F is a control function (Value may be 0 or 1)

$$G_{d,cpc} = \begin{cases} G_d & \text{if } (\beta + \theta_c) \leq 90^\circ \\ \frac{G_d}{2} (1/C + \cos \beta) & \text{if } (\beta + \theta_c) \geq 90^\circ \end{cases} \quad (19A)$$

$$= \begin{cases} G_d & \text{if } (\beta + \theta_c) \leq 90^\circ \\ \frac{G_d}{2} (1/C + \cos \beta) & \text{if } (\beta + \theta_c) \geq 90^\circ \end{cases} \quad (19B)$$

$$G_{g,cpc} = \begin{cases} 0 & \text{if } (\beta + \theta_c) \leq 90^\circ \\ \frac{G_g}{2} (1/C - \cos \beta) & \text{if } (\beta + \theta_c) \geq 90^\circ \end{cases} \quad (20A)$$

$$= \begin{cases} 0 & \text{if } (\beta + \theta_c) \leq 90^\circ \\ \frac{G_g}{2} (1/C - \cos \beta) & \text{if } (\beta + \theta_c) \geq 90^\circ \end{cases} \quad (20B)$$

The first term in Eq. (17) is the beam contribution to Sr, the second is the contribution of the diffuse and the third is the contribution of the ground-reflected radiation. In the first term,  $G_{b,cpc}$  is the beam radiation on the aperture that is within the acceptance angle,  $\tau_{c,b}$  is the transmittance for beam radiation of any cover which may be placed over the concentrator array and  $\alpha_b$  is the absorptance of the receiver for the beam radiation. The factor  $\tau_{cpc,b}$  is the transmittance of the CPC which accounts for reflection losses of beam radiation and is a function of the average number of reflections. The factors in the terms of diffuse and ground-reflected radiation are analogous to those which for the beam radiation.

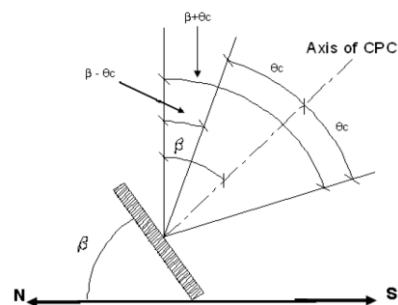
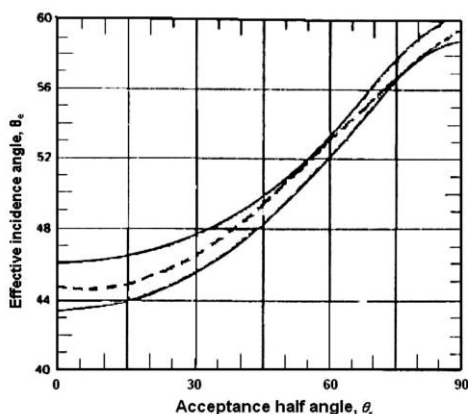


Fig.11 Projection on a north-south plane of CPC acceptance angles and slope for a CPC on an east-west axis

The ground-reflected radiation is only effective if  $(\beta + \theta_c) \geq 90^\circ$ , i.e., if the receiver sees the ground. The angles are shown in Fig. 10. Eq. (3.19A) to (20B) account for the contribution or lack of the ground-reflected radiation which is assumed to be isotropic. Fig. 11 shows the acceptance angle of a CPC on a vertical north-south plane for a CPC oriented east-west. Two angles,  $(\beta - \theta_c)$  and  $(\beta + \theta_c)$ , are the angles from the vertical in this plane to the two limits describing the acceptance angle. It has been shown that the following condition must be met in order for the beam radiation to be effective.

$$(\beta - \theta_c) \leq \tan^{-1}(\tan \theta_z \cdot \cos \gamma_z) \leq (\beta + \theta_c) \tag{21}$$

It is convenient to introduce the control function  $F$  in Eq. (18) which is 1 if the criterion of Eq. (21) is met and 0 otherwise. If the beam radiation is incident on the aperture within the acceptance angle,  $F = 1$  and the beam radiation term will be included in the calculation of  $S_r$ .



**Fig. 12** Equivalent incidence angles for reflections undergone for isotropic diffuse radiation for a CPC as a function of acceptance half angle

A CPC collector will probably have a transparent cover over the array of the reflectors. This serves both to protect the reflecting and absorbing surfaces and to reduce thermal losses from the absorber. The beam and diffuse radiation effectively entering the CPC are reduced by the transmittance of the cover  $\tau_c$ . Only part of the incident diffuse radiation effectively enters the CPC, and that part is a function of the acceptance angle. A relationship between the mean angle of incidence of effective diffuse radiation and the acceptance half-angle  $\theta_c$  is shown in Fig. 12. This is based on the assumption that the diffuse radiation is isotropic. The relationship depends on the nature of the cover system, and the figure shows a band of solutions including one and two covers, with refractive indices of 1.34 and 1.526. An equation for the equivalent incidence angle  $\theta_e$  (the dashed line) is:

$$\theta_e = 44.86 - 0.0716 \theta_c + 0.00512 \theta_c^2 - 0.00002798 \theta_c^3 \tag{22}$$

Thus for a CPC with  $\theta_c = 20^\circ$ , the mean angle of incidence of effective diffuse radiation is  $45^\circ$  and the transmittance of the cover for this radiation is that of beam radiation at  $45^\circ$ . The terms  $\tau_{cpc,b}$ ,  $\tau_{cpc,d}$  and  $\tau_{cpc,g}$  in Eq. (17) are transmittances of the CPC that account for the specular reflectance of the concentrator and the average number of reflections. The terms are usually treated as the same, and an appropriate value to be applied to all three of them is estimated from the number of reflections  $n$  from Fig. 7 and the transmittance of CPC by the equation Rabl A., Goodman N. B. and Winston R.:

$$\tau_{Cpc} = \rho^n \tag{23}$$

Here it is assumed that end effects are negligible or that the ends are highly reflective. The absorptance  $\alpha_b, \alpha_d$  and  $\alpha_g$  of the receiver surface depend on the angles of incidence of the radiation on the surface. The angles of incidence vary depending on the angle of incidence of the radiation on the aperture of the CPC, the number of reflections undergone by the radiation and the shape of the reflecting and receiving surfaces. If the average number of reflections is small, as it will be for large acceptance angles, then as a first approximation the absorptance can be taken as that corresponding to the angle of incidence of the effective radiation on the aperture of the CPC; however, this will generally result in overestimation of  $\alpha$ . Due to lack of design information, there may be no alternative.

Pinazo J. M., Canada J. and Arago F. have derived an analytical expressions for the projected incidence angles for a two-dimensional compound parabolic concentrator solar collector. For a CPC the fraction of the incident rays on the aperture at an angle  $\theta$ , which reaches the absorber, depends only on the transverse projected incident angle. A mathematical expression for transverse and axial projected angles have been developed to determine the times at which acceptance of the sun's beam radiation begins and ceases for a CPC consisting of arbitrary orientation. Hence transverse incident angle is to be considered instead of  $\theta$  for estimation of energy collected by the CPC.

Siala F. M. and Hooper F. C. developed a model by single scattering approximation in a typical application, in which the fraction of diffuse radiation intercepted by the receiver of a compound parabolic concentrator is computed. The proposed model is compared to the isotropic model of the diffuse radiance by using each separately to evaluate  $f_{acc}$ , the fraction of the diffuse radiation incident on the aperture of a compound parabolic concentrating (CPC)



collector which is intercepted by the absorber. The CPC, the acceptance half-angle of which is  $\theta_c$ , is assumed to be oriented such that the trough axis is aligned in the east-west direction and the aperture is inclined at an angle  $\beta$  from the horizontal. The factor  $f_{acc}$  is a function of the acceptance half angle, the aperture inclination angle and the angular distribution of the diffuse radiance. It is seldom explicitly mentioned that, in the case of an isotropic distribution the expression  $f_{acc}=1/C$  Rabl A, is only valid if  $\beta=0^\circ$ . For the general case they suggested the following equations. Fig. 13 shows values for  $f_{acc}$  calculated using the isotropic model, and also for the semi-empirical model (including first-order scattering only).

$$f_{acc} = \begin{cases} \frac{2}{C(1 + \cos \beta)} & \text{if } (\beta + \theta_c) \leq 90^\circ \\ \frac{1 + C \cdot \cos \beta}{C(1 + \cos \beta)} & \text{if } (\beta + \theta_c) > 90^\circ \end{cases} \quad (24)$$

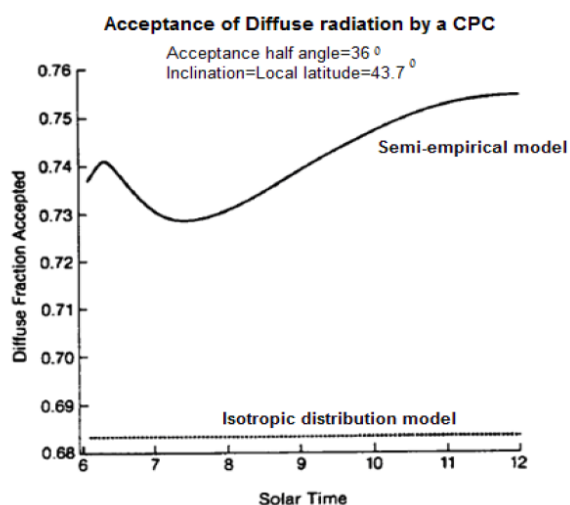


Fig.13 The acceptance of diffuse radiation by a CPC collector incident Rabl A

Optical efficiency of the CPC

The definition of the optical efficiency is the efficiency by which the concentrator can reflect and concentrate the radiation.

Mosalam Shaltout M. A., Medhat M., and Hadi Y. A., [38] have studied the efficiency of the Compound Parabolic Concentrator (CPC) and its photovoltaic applications. Optical efficiency can be given by

$$\eta_o = \phi_i \cdot \rho^n \quad (25)$$

or

$$\eta_o = \phi_i \cdot \tau_{cpc} \quad (26)$$

The relation:

Where,  $\phi_i$  is the fraction of  $t$  is the fraction of total insolation accepted by the CPC;  $\rho$  is the

reflectivity of the concentrator plate for a single reflection;  $n$  is the number of reflections undergone by the concentrator;  $\tau_{cpc}$  is the transmissivity/overall reflectivity of the concentrator for  $n$  reflections. The factor  $\phi_i$  depends on the turbidity of the atmosphere and on the acceptance angle. On clear days, values of  $\phi_i \approx 92\%$ , for threefold and  $\phi_i \approx 88\%$  for tenfold concentration have been measured Rabl A..

Rabl A., O’Gallagher J. and Winston R. [39] had designed and tested the CPCs for their efficiency. The fraction of the hemispherical irradiance  $I_h$  which falls within the acceptance angle of a CPC collector depends on its concentration and on the haziness of the atmosphere, ranging from about 92 percent for a 3X (90 percent for a 6.5X) on clear days to 80 per cent or less on hazy days. Therefore, the collector performance can display considerable scatter when analyzed in terms of hemispherical irradiance  $I_h$  under different weather conditions. To minimize this scatter they have tested solar collectors under reasonably clear sky conditions. The insolation within the acceptance angle of a CPC of geometric concentration  $C$  was approximated by,

$$I_c = I_b + \frac{1}{C} I_d = I_h + \left(\frac{1}{C} - 1\right) I_d \quad (27)$$

Where,  $I_b$  is the beam (also called direct) component of insolation. The efficiency should therefore be nearly independent of  $I_d/I_h$  if it is referred to  $I_c$  instead of  $I_h$ . So it is suggested that the efficiency  $\eta_h$  with respect to hemispherical/global irradiance be corrected according to mentioned below.

$$\eta_{h,standard} = \frac{1 + \left(\frac{1}{C} - 1\right) \left(\frac{I_d}{I_{h,standard}}\right)}{1 + \left(\frac{1}{C} - 1\right) \frac{I_d}{I_h}} (\eta_h) \quad (28)$$

The above equation is suggested with a clear day ratio of  $I_d/I_{h,standard} = 0.11$  to reduce the scatter. For all of the concentrator system with a cover of transmission  $\tau_c$  and an absorber/receiver with an effective absorption coefficient  $\alpha_r$ , the optical efficiency can be calculated from O’Gallagher J. and Winston R.

$$\eta_o = \phi_i \cdot \tau_c \cdot \tau_{cpc} \cdot \alpha_r \quad (29)$$

Radiation Distribution on the Absorber of the CPC

Macedo I. C. and Faria Alves C. L.had carried out a work with ray tracing to verify the influence of the concentration ratio, truncation, beam incidence angle, absorber height, non-secularity and reflectivity of the mirrors on the radiation intensity distribution. The behavior for diffuse non-isotropic radiation is also considered. The

validity of the proposed models is verified with experimental results in some compound parabolic collectors. They have concluded that the radiation intensity distribution becomes more uniform for concentration ratio above 3.0. Moreover it is concluded that better distribution is achieved for incident angles near to  $\theta_c$  than normal incident (i.e.  $\theta_c = 0$ ).

Smyth M., Zacharopoulos A., Eames P. C. and Norton B. have developed an experimental method for predicting the solar radiation intensity distribution incident on the absorber of a line-axis Compound Parabolic Concentrator (CPC). The insolation level and corresponding temperature response were recorded for six different locations in front of a solar simulator. A pyranometer was used to measure the point radiation intensity and a T-type thermocouple to measure temperature at one second intervals. A relationship has been derived that correlates insolation intensity with rate of temperature rise based on first order time/temperature response curves obtained from thermocouples exposed to direct solar radiation. Employing this technique the energy flux distribution on the absorber of three line axis CPCs has been determined. The results have been validated with at two dimensional raytrace analysis. The Fig. 14 shows the solar energy flux distribution for a CPC with flat absorber having half acceptance angle of  $30^\circ$  and geometrical concentration of 1.8.

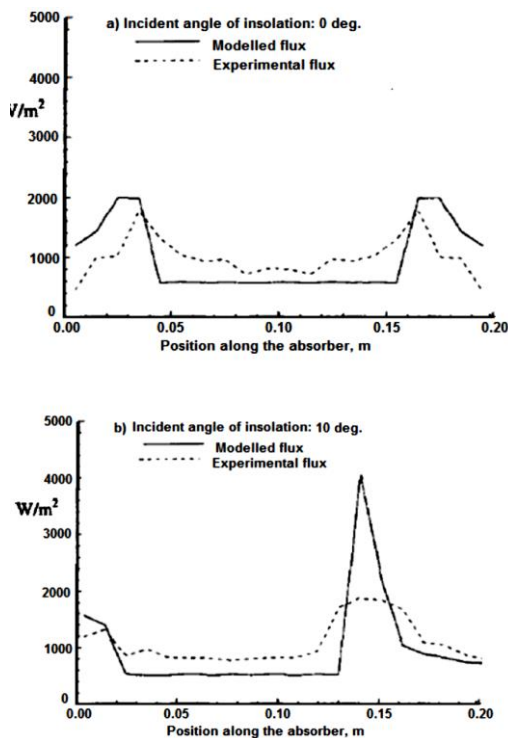


Fig. 14 experimentally determined and ray trace predicted energy flux distributions along the absorber of a symmetric CPC with flat absorber for (a)  $0^\circ$  and (b)  $10^\circ$  incidence angle of solar radiation

Optimum half acceptance angle for the CPC

Suzuki Akio and Kobayashi Shigeo have studied optimum acceptance angle of a compound parabolic concentrator (CPC) by proposing the use of an insolation model developed. The insolation consists of two components; diffuse and direct. The direct radiation is supposed to be distributed in the field within  $\pm 23.5^\circ$  of declination on the celestial hemisphere and the diffuse radiation is assumed to have uniform irradiance. This yearly insolation model suggests that the optimum half acceptance angle at the two-dimensional CPC becomes  $\theta_c = 26^\circ$  irrespective of the change of the diffuse radiation fraction. This result leads them to the conclusion that, almost all over the world, a common CPC could be used as an optimum concentration for many solar radiation collecting systems.

5. Other developments in CPC

Sea Shell Concentrator

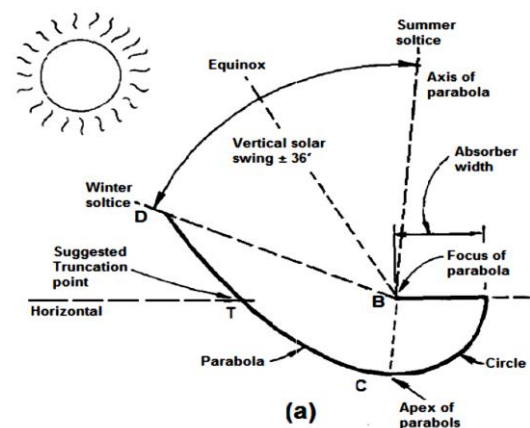


Fig. 15(a) Stationary Sea Shell collector with variable concentration, with maximal output in summer  $R_{ab1}$

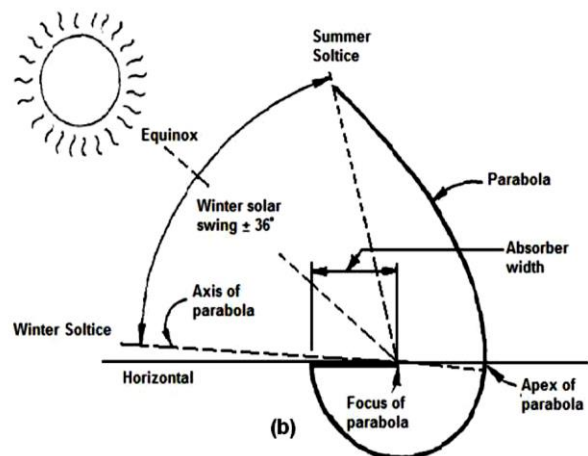


Fig.15 (b) Stationary Sea Shell collector with variable concentration, with maximal output in winter

The concentrators possess uniform concentration for all angles of incidence less than the half acceptance angle. For heating and cooling applications, however,

the load varies with the seasons, and a collector with variable output might be more appropriate. The concentrators shown in Fig.15 (a) and (b) have this property. They consist of a single parabola CD whose axis is parallel to one of the extreme rays and whose focus is at the edge B of the absorber; the parabola concentrates all radiation incidents on the aperture BD with incident angle less than half acceptance angle onto the surface BC.

The examples shown here have an acceptance half angle of 36°, and thus they are truly stationary with a collection time of at least 7 hr per day. Their concentration is 1.7 at normal incidence, but varies from zero (winter for (a), summer for (b)) to 3.4 (summer for (a), winter for (b)). This sea shell collector is of course constructed according to the same principle as the other ideal concentrators; no radiation emitted by the absorber is allowed to escape from the collector outside its acceptance angle, as is readily verified. The change in concentration can be varied by truncation to fit the demand curve for a particular user. For example, with the truncation point at T in Fig. 15(a) the concentration ranges from 0.7 to 1.7 with a mean value of 1.5 at zero incident angles, Rabl A.

Asymmetric concentrator

The ordinary CPC (Fig. 2) and the Sea Shell (Fig. 15) are special limiting cases of a general class of asymmetric concentrators sketched in Fig.16 Rabl A., [8]. The focal length of both the parabolas is not same as ordinary CPC. The axis of the left (right) parabola subtends an angle  $\phi_l$  ( $\phi_r$ ) with the absorber normal. Fl (Fr) is the focus of the left (right) parabola. The acceptance angle is  $2\theta_c = \phi_l + \phi_r$ , and the geometric concentration is  $C = 1/\sin\theta_c$ . The effective concentration varies from a minimum at  $\theta_i = \phi_r$ , to a maximum at or near  $\theta_i = \phi_l$ , due to the change in projected aperture area normal to  $\theta_i$ . The ordinary CPC corresponds to  $\theta_c = \phi_r = \phi_l$  and the Sea Shell to  $2\theta_c = \phi_l$  and  $\phi_r = 0$ .

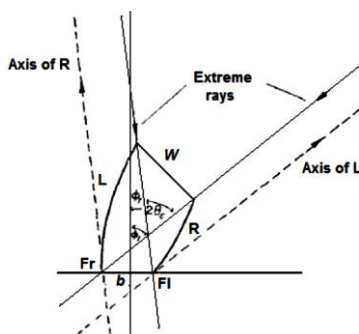


Fig. 16 Asymmetric ideal concentrator

MaReCo: Maximum reflector collector

An asymmetrically truncated non-tracking compound parabolic concentrator type collector design concept has been developed and optimized for northern

latitudes Adsten M., Helgesson A. and Karlsson B.. At high latitudes the annual solar radiation is asymmetric over the year, implying that the collector should be asymmetrically truncated to maximize the yield. These conclusions have led to the development of a design concept with an asymmetrically truncated CPC-collector with a bi-facial absorber that does not need any tracking. Since the main objective was to maximize the reflector to absorber area for a given ground area, this collector is called a Maximum Reflector Collector, MaReCo. In addition to the aim of reducing the cost of solar energy the intention is also to indicate the possibility of special collector designs adapted to various installation- and load conditions. The general form of the MaReCo reflector trough is designed with two parabolas with their optical axes defining the lower and upper acceptance angles. The reflector consists of three parts as shown in Fig. 17. Part A is the lower parabolic reflector extended from point 1 to 4, Part B is the connecting circular reflector extended from point 1 to 2, and Part C is the upper parabolic reflector extended from point 2 to 3. The cover glass is found between points 3 and 4. The position of the cover glass varies along the extended parabola depending on the truncation.  $\beta$  is the aperture tilt.

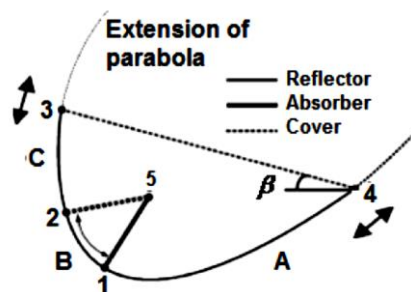


Fig. 17 Sketch of the basic MaReCo design

This parabola has its optical axis along the upper acceptance angle and its focal point on point 5 (the top of the absorber). Part B is a circular part between points 1 and 2. This circular part B transfers the light onto the rear side of the absorber. It replaces an absorber fin between focus and point 2 (indicated by a dotted absorber between points 2 and 5) with the rear side of the absorber between point 1 and 5. The lower tip of the absorber can be placed anywhere between points 1 and 2. Part C is a parabolic upper reflector between points 2 and 3. The parabola part A has its optical axis along the lower acceptance angle and its focus at point 5. The position of the cover glass, the truncation, (i.e. the position of points 3 and 4 along the extended parabolas) is determined by varying the position of the reflector sheet along the extended parabolas to find the position where maximum annual irradiation, given by the annual radiation distribution, onto the aperture is obtained. When designing the collector prototypes this was achieved by sliding a reflector sheet of a certain width along the parabola/circle form shown in Fig. 17 and measuring the distance between point 3 and 4, i.e. the width of the cover glass and the aperture tilt defined in Fig. 17.

### 7. Convection heat transfer in CPC

Abdel Khalik and Randall evaluated natural convection heat transfer coefficient between absorber and cover by using finite element technique. They have studied natural convection in inclined 2-D CPC. Hsieh C. K. had developed a mathematical formulation to study thermal processes in a 2-D CPC. The predicted results were compared with experimental results. Tatara and Thodos studied experimental natural convection within a CPC enclosure. Prapas et al. did experimental study of free convection in CPC cavities. Chew and et al. and performed experimental and numerical study of natural convection in CPC cavities. Eames P. C. and Norton B., presented a validated model of heat transfer in CPC collectors. This model combines 2-D steady state finite element analysis of convective heat transfer and ray trace technique. Eames P. C. and Norton B. performed a detailed parametric analysis of heat transfer by using this method. Ronnelid M. and Karlsson B. experimentally investigated overall heat loss for 2D CPC with flat plate absorber. It is concluded that an air gap of 2 cm between the reflectors and cover increases the heat loss of the CPC. Shah P. K. and Patel L. N. developed the analytical method to determine the different temperatures of the CPC components. They have also predicted the thermal performance of the ideal CPC. Shah P. K. and Patel L. N. Pramuang S. and Exell R. B. H. by transient test evaluated the linear and nonlinear heat loss coefficients for a 2D CPC with flat absorber and concentration ratio of three. Othman M. Y. Hj. and et al. developed steady state model to predict thermal and electrical performance of PV/T CPC collector with fins. The predicted results were validated with experimental results.

### 8. Photovoltaic and Thermal Solar Energy Concentrators

The need of energy in the world is increasing, especially because of the technology and the growth in the world's population. The total energy consumed in the form of coal, gas and oil, nuclear, hydro and renewable energy sources is known as primary energy. This energy consumption was at 488.10<sup>18</sup> Joules or 488 Exa-Joules (EJ) in 2005, it had grown from 385 EJ at over 2.4% of Compound Annual Growth Rate (CAGR) since 1995 (fig. a). Searching for alternative energy sources became a necessity. Because of the limitation of fossil fuel's quantity, renewable energy sources, used separately or in hybrid structure, are introduced to replace the pollutant nonrenewable energy [68-85]. Energy storage devices and systems for renewable and nonrenewable production energy are also treated in the literature. Generally, there are three types of solar energy conversion: Photovoltaic (PV) Conversion which can be obtained by increasing the potential energy of the electron, Photochemical Conversion, and Solar Thermal Conversion, which requires an increase in kinetic energy and heat generation (fig. b). PV needs materials that have various energy levels separated from each other which can exist in semi-conductor materials. Photovoltaic energy is one of the most

interesting solutions, but it is still too expensive. However, its cost can be reduced significantly by using Luminescent Solar Concentrators (LSC). LSC can decrease the number of solar cells needed to produce an amount of energy by concentrating the light in a smaller area (fig. c). Using of multifunction cell increases the value of energy conversion efficiency from 20% to more than 30%. In addition, the same principle of concentrating the light in a smaller area was used in thermal concentrators.

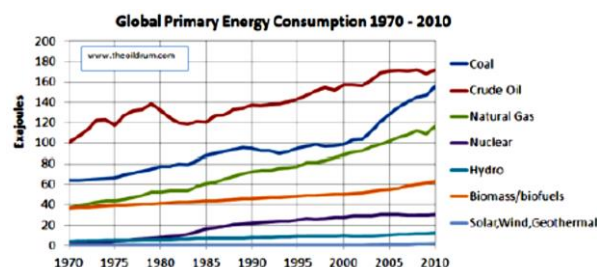


Figure a. World primary energy consumption in EJ

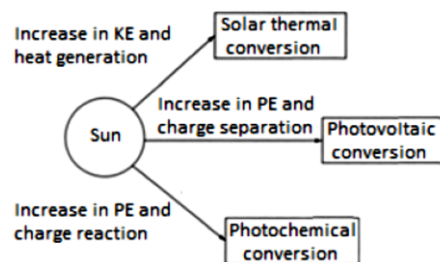


Figure b. various routes of solar energy conversion

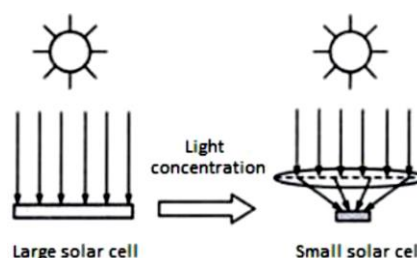


Figure c. Schematic representation of light concentration demonstrating the use of smaller cell area

### 9. Applications of CPC

Looking to the advantages of CPC like no continuous tracking, acceptance and collection of diffuse radiation, ideal concentration, negligible effect of curvature errors of reflectors on concentration etc., the CPC become most popular. CPC generates temperature below 100<sup>0</sup> C at flat absorber with concentration ratios from 1.7 to 2.0. For higher concentration ratio it generates up to 300<sup>0</sup> C. The few practical applications of CPC are listed below.

- (1) Water heating
- (2) Space heating
- (3) Industrial process drying and heating



- (4) Process steam generation
- (5) Concentrated photovoltaic/Thermal application
- (6) As generator heat source for vapour absorption refrigeration system
- (7) CPC type integrated collector storage water heating system (Tripanagnostopoulos Y. et al., [113])
- (8) Second stage concentrator with parabolic mirror or Fresnel lens as first stage concentrator for high temperature applications.
- (9) High flux solar furnaces have demonstrated the effectiveness of using concentrated solar energy.
- (10) Use of CPC as advanced non-imaging secondaries to pump lesser and produce fullerenes (potentially useful new forms of molecular carbon).
- (11) Asymmetric CPC could be used for building facade integrated with photovoltaic (Mallick T. K. et al., [114]).
- (12) Used for high temperature applications like, surface treating with sunbeams, solar thermal production of zinc, high temperature thermochemistry, high flux solar furnace etc.
- (13) Daylighting is the most efficient use of solar energy. After a long time of neglected daylight it is being rediscovered in modern architecture. It can help to save energy. Recently a new device: The CPC Sun Protection Element (CPCSPE) has been developed by Goswami Y. D. and Boer K. W. It can replace roof overhangs or windows in roofs. It is placed in such a way that beam radiation enters the aperture outside the acceptance angle. Thus it provides protection against glare and overheating but it transmits diffuse light, so the rooms get more daylight. Edwards L. and Torcellini P. have reviewed the effects of natural light on building occupants besides the benefits of energy saving.

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