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Ray tracing for optimization of compound parabolic concentrators for solar collectors of enclosed design

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Abstract: We present our developments in computer simulations and optimization of compound parabolic concentrators (CPCs) for solar heat collectors. Issues of both the optical and thermal optimization of CPC collectors of enclosed design are discussed. Ray tracing results for a CPC with a V-shaped absorber are presented. A range of optimal values for the apex angle of a V-shaped absorber is proposed for a CPC collector of typical design.

Key words: Renewable energy, solar heat collector, ray tracing, compound parabolic concentrator

1. Introduction

Compound parabolic concentrators (CPCs) are advanced technological solutions developed for making efficient solar heat collectors for a variety of applications [1–6]. CPC collectors are more productive as compared to common flat-plate systems [3]. At the same time, they are simpler, less expensive, and more reliable than parabolic concentrators (being of either 2D "trough" or 3D "dish" design), since the latter requires accurate and expensive sun-tracking devices, precise mirror shaping, complicated maintenance, and so on [4–7].

The basic advantages of CPC collectors, which were invented in 1966 [8,9], originate from the fact that they can be used as nontracking collectors. Along with the simplicity of CPC design, this leads to lower cost of fabrication, maintenance, and usage [3]. Though nontracking systems are less suitable for producing high-temperature steam for generating electricity with turbines, they became definite leaders in mid-temperature heat generation as needed for many industrial and domestic purposes [3–6]. Another advantage of CPCs is their ability of capturing diffused light that comes from different directions in the sky [5–10].

CPC collectors are now well developed. However, when optimizing CPC design with account of both the optical and thermal processes, the collectors could further be improved [11]. A more advanced design means, though, a more expensive kind of collector. Therefore, a practical approach should be to find a reasonable balance between the CPC price and complexity. This means that we should be able to generate an optimal CPC design on demand, i.e. tailored for a particular application rather than a universal design for all circumstances. Our generic aim is, therefore, to develop a simulation system capable of generating an optimal design of nontracking CPC collectors for the given set of requirements being presented.

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In this paper, we report on our simulations developed for CPC structures of nontracking solar heat collectors, which should be capable of generating the heat in the form of hot water or steam supply at temperatures ranging from $t = 100$ to $t = 150$ °C. Specifically, we describe our development of a ray-tracing model for enclosed CPC collectors (those providing a better thermal insulation of absorbers) that is needed as a key component of generic simulation software being created for the design of efficient CPC collectors.

The term "enclosed" means here a kind of collector that has a transparent cover (a window) at the entrance aperture and contains the absorber (of arbitrary shape) suspended inside the CPC and surrounded by mirror surfaces on both sides and at the bottom. Enclosed collectors allow us to reduce thermal losses and provide environmental protection for both the mirrors and the absorber.

2. Benefits and drawbacks of enclosed CPC collectors

CPC collectors are optimized mainly with respect to their optical properties. In this sense, CPC structures are rated as being ideal nonimaging collectors [1–3]. Conventional CPC analysis is made, though, with a number of simplifying assumptions that neglect technological features of real design, technical limitations of their fabrication, and the actual conditions of CPC operation.

Typical analysis is based on the study of an ideal system of CPC mirrors when the light enters the system through the entrance aperture with no losses and propagates to the exit aperture where it is fully absorbed by an ideal absorber filling the entire aperture cross-section. The light concentration properties of such a system are indeed ideal and nothing can be improved should the ideal system could be implemented [1–7].

In this paper, we consider trough-like CPC collectors that have a CPC profile defined in the cross-section plane XY orthogonal to the trough axial direction OZ. The light collection efficiency of CPCs of this kind is specified by the light concentration factor K as defined in the XY plane. The maximum concentration factor of an ideal CPC with full-height mirrors is found as $K = 1/\sin\theta$, where θ is the acceptance half-angle of the CPC collector according to conventional definition [3–7].

Real CPC collectors suffer from imperfections that reduce CPC efficiency. Thus, the aim of practical design is to minimize the losses caused by imperfections when taking into account restrictions imposed by the type of design, material properties, cost considerations, and so on.

Enclosed CPC collectors have certain benefits and drawbacks as compared to open structures. The main benefits are the better heat isolation and improved structural strength of the collector due to the closed geometry of the CPC cell formed by the mirror walls and the dielectric window at the entrance aperture. Particularly important is the reduction of air convection and heat losses through the entrance aperture covered with a dielectric window. Enclosed design also ensures environmental protection of mirrors and absorbers inside the CPC cell.

An obvious drawback of enclosed CPCs is the higher level of optical losses due to the light reflection from the dielectric window that grows with the angle of light incidence and rapidly increases in the morning and evening hours. In addition, there are other losses common to all structures such as nonideal reflectivity of mirrors, imperfect light absorption in the absorber (particularly at the grazing incidence being typical for CPC), noticeable infrared emission from the absorber to the sky through the same CPC optics due to limited spectral selectivity of real absorbers, and so on.

In total, the benefits and drawbacks may partially balance each other, so a good design should strengthen the benefits while reducing drawbacks. This is achieved through optimizing the values of design parameters that could be set free or varied within certain technical bounds.

For an ideal CPC, there is only one design parameter to be defined, which is the acceptance half-angle θ (assuming the exit aperture size is defined by the standard size of the absorber). Values of θ are often chosen in the range of 15–30 degrees that yields a reasonably good concentration factor $K = 2 - 4$ and eventually requires either none or, at most, a few seasonal repositionings of nontracking CPC with respect to the horizon.

Real CPC collectors are characterized by many parameters that have to be optimized simultaneously. This can be achieved through computer simulations using relevant simulation models and software. There are publications that describe recent progress in this direction [11]. However, there is no dedicated software publicly available for CPC design and optimization. Therefore, we developed proprietary simulation modules that allowed us to carry out basic simulations of some CPC structures of interest.

We consider a trough-like CPC of the cross-section as shown in Figures 1 and 2. Accepting some parameters as being fixed by the type of design (e.g., the height of CPC section h and the width w of the absorber strip attached to the water-carrying pipe), we obtain a number of other parameters that have to be optimized. Simulations are organized in two parts, the optical and the thermal ones, with relevant iterations between them. Whereas optical modeling is straightforward and the power received by the absorber could be found easily, thermal losses are hard to evaluate precisely [5,7,11]. The main losses typically occur in the CPC due to the heat leakage from the absorber and water-carrying pipes, which are always exposed to the outer space.

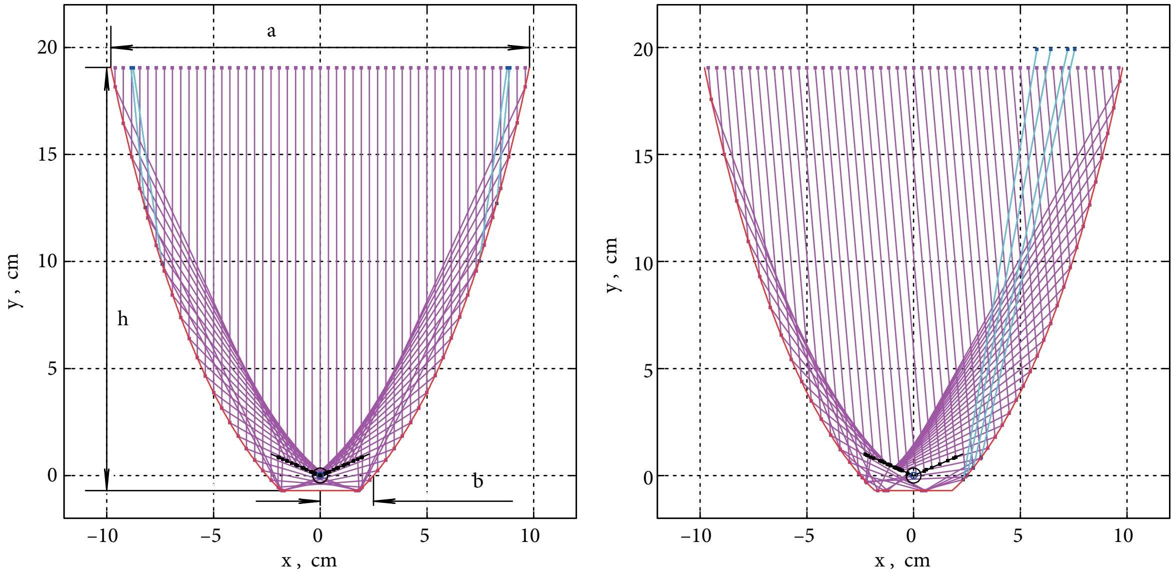

Figure 1. Ray tracing in an enclosed CPC with a V-shaped absorber at the light incidence angles (a) $\theta_i = 0$ and (b) $\theta_i = 5$ degrees with respect to the CPC axis. CPC parameters are $h = 20$ cm, $a = 19.6$ cm, $b = 2.5$ cm, $w = 5$ cm, $h_b = 0.7$ cm, $x_t = 2.3$ cm, $y_t = 1.0$ cm, and $\theta_m = 9$ degrees.

There are two basic mechanisms of these losses, the infrared radiation of energy from the absorber and the heat conductivity through the air and CPC constructive elements. The mechanisms could be described by the relevant terms in the energy balance equation, one being proportional to the fourth power of T and the other linear in T, where T is the temperature of the hot element, as shown, e.g., in [11].

There is an efficient method of reducing the infrared radiation losses, which is based on the use of selective absorption coatings [12]. Spectral selectivity of absorption allows one to reduce the infrared absorption and emission of radiation (e.g., down to 5%) while preserving a strong absorption in the optical band (e.g., about

95%). The role of spectral selectivity is lower at the higher level of light intensity [11], yet it remains an essential factor in optimizing the overall efficiency of solar collectors.

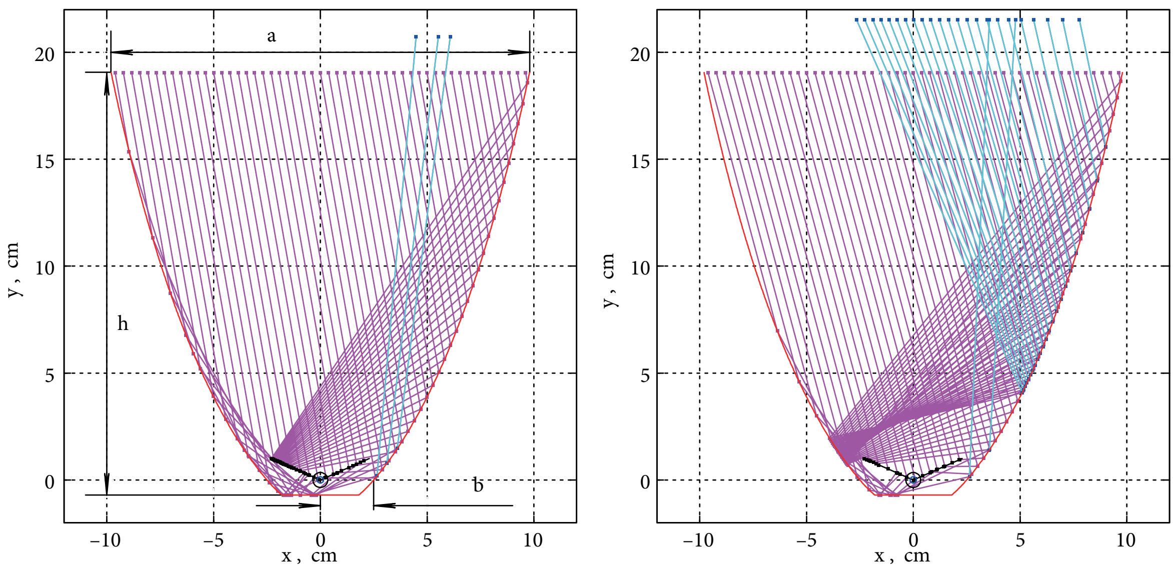

Figure 2. Ray tracing in an enclosed CPC with a V-shaped absorber at the light incidence angles (a) $\theta_i = 10$ and (b) $\theta_i = 15$ degrees with respect to the CPC axis. CPC parameters are $h = 20$ cm, $a = 19.6$ cm, $b = 2.5$ cm, $w = 5$ cm, $h_b = 0.7$ cm, $x_t = 2.3$ cm, $y_t = 1.0$ cm, and $\theta_m = 9$ degrees.

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In this paper, we would like to emphasize that there are other mechanisms of selectivity in the hot elements of the CPC exposed to the environment and therefore providing inevitable energy sink for the collector. One of these mechanisms could be called the selectivity in space (or, alternatively, the angular selectivity) and the other one is the selectivity in time.

The matter is, when considering the spectral selectivity of absorbers, we should take into account that absorption in the optical band is significant for nearly all directions of the light incidence (when decreasing with the incidence angle, it usually follows the Lambertian law such that the absorption is proportional to the cosine of the incidence angle). On the contrary, selective surfaces in the infrared are essentially specular such that the infrared energy is radiated mainly along the normal to the absorber surface.

This creates the angular selectivity of absorbers (in addition to spectral selectivity) that could be used for further optimization of CPC structures. It is clear that should the frequency selective absorber be tilted slightly away from the optical path to the sky, the infrared radiation would not escape the CPC that easily, and therefore the radiation losses would be reduced whereas the optical absorption remains nearly the same.

In a similar way, we could also play with the extraction of useful heat from the CPC collector. Once the collector efficiency is higher at the lower temperature of hot elements, we should limit the target temperature of the heat carrier (mid-temperature hot water) in the storage tank when the light intensity is low and then occasionally switch to the regime of further heating of some part of the earlier accumulated heat carrier to the higher temperature level when the light intensity is sufficient. This kind of two-stage (or multistage) heat accumulation and usage creates, essentially, an additional mechanism of selectivity, which is the selectivity in time.

At this stage of research, we completed the development of a proprietary ray-tracing simulation module for CPC cells that allows us to keep full control over the optical part of modeling and the energy supply into the system. This has been used for provisional optimization of the basic design solutions outlined above. In the next stage, thermal analysis will be included by using available software packages for solving the heat exchange problems in various kinds of CPC cells. Eventually, optimization of CPC cells will be completed with the required parameters of heat storage and water supply.

3. Ray tracing in a CPC collector with a V-shaped absorber

Ray-tracing simulations are based on the reflection laws presented in a vector form. Software implementation of ray tracing is straightforward, though it requires special care when searching for intersection points of rays and surfaces. The benefit of in-house implementation is that it provides complete control over any detail of simulations, including variation of reflection and absorption coefficients, arbitrary shape of mirrors, optimization of shape, and a possibility of generalization for answering any nonconventional questions.

The idea of using spatial (angular) selectivity of frequency selective absorbers could be implemented through the use of different shapes and orientations of absorbing elements in a CPC structure. A possible solution is the use of a V-shaped wing absorber attached to the water-carrying pipe along the vertex (see Figures 1 and 2). Assuming the standard total width w of the absorber strip (w = 5 cm), we could place the absorber at different positions of vertex and different tilts of absorber wings inside the CPC structure. As an example, the absorber of symmetrical V-shape shown in Figures 1 and 2 is specified by coordinates $x_t = 2.3$ cm and $y_t = 1.0$ cm of the top-right absorber edge while the vertex is placed at the origin of the coordinate frame.

In our example, we consider the amount of light power P_{abs} captured by an ideal V-shape absorber as a function of the light incidence angle θ_i when the absorber is placed inside the CPC having an additional mirror surface at the bottom. For simplicity, we assume a standard CPC design for the side walls ($0 < y < h_t$) defined as the pieces of two parabolic mirrors with focal points at ($x_{FR} = --b$, $y_{FR} = 0$) and ($x_{FL} = b$, $y_{FL} = 0$) for the right-hand-side and left-hand-side mirror, respectively [10].

The mirror below the x-axis ($-h_b <$ y < 0) is shaped as a vertical parabola smoothly connected to the CPC side mirrors at (x_{FR}, y_{FR}) and (x_{FL}, y_{FL}) and having the bottom part cut off at the level of $y = -h_b$ so as to be replaced by the flat mirror for improving the light collection in this kind of design. In this example, we accept the values of $b = 2.5$ cm, $h_b = 0.7$ cm, total height of CPC section $h = h_b + h_t = 20$ cm, and tilt of each mirror towards the y-axis $\theta_m = 9$ degrees. As a result, we obtain the CPC aperture of $a = 19.6$ cm and acceptance half-angle $\theta = 9$ degrees that specify a CPC cell of practical size and reasonable performance.

Thanks to the V-shape of the absorber, which is made suspended in the CPC so as to avoid thermal contact with mirror surfaces, we could achieve both better light collection and, at the same time, lower thermal losses caused by the heat sink from the absorber to the side mirrors. The heat sink of this kind would always exist in a more conventional design when the flat absorber fills in the CPC exit aperture at $y = 0$, $--b < x < b$ such that it makes thermal contact with the walls and requires additional heat isolation from the bottom side.

There is, though, a certain loss of power in the new design due to the light reflection back to the sky in the process of multiple reflection and formation of caustics near the bottom mirror. However, the effect could be reduced through optimization of the CPC structure.

As an illustration of the effects involved, Figures 1 and 2 show the ray tracing in the CPC computed with our simulation module. Figures 1a, 1b, 2a, and 2b show gradual increase of losses due to reflection with increasing light incidence angle and, eventually, transition to significant losses when the incidence angle exceeds the acceptance half-angle defined for this structure.

Further insight into the processes involved could be obtained from Figure 3a, which shows the relative power P_{abs} captured by an ideal V-shaped absorber in the given CPC as a function of the light incidence angle θ_i at various tilts θ_w of absorber wings with respect to the x-axis (power is normalized to the incident light intensity so that P_{abs} is found as the ratio of numbers of rays hitting the absorber and entering the CPC, respectively, assuming the light flux in the direction of incidence is constant and the number of rays per unit cross-section of the light beam is proportional to the light flux).

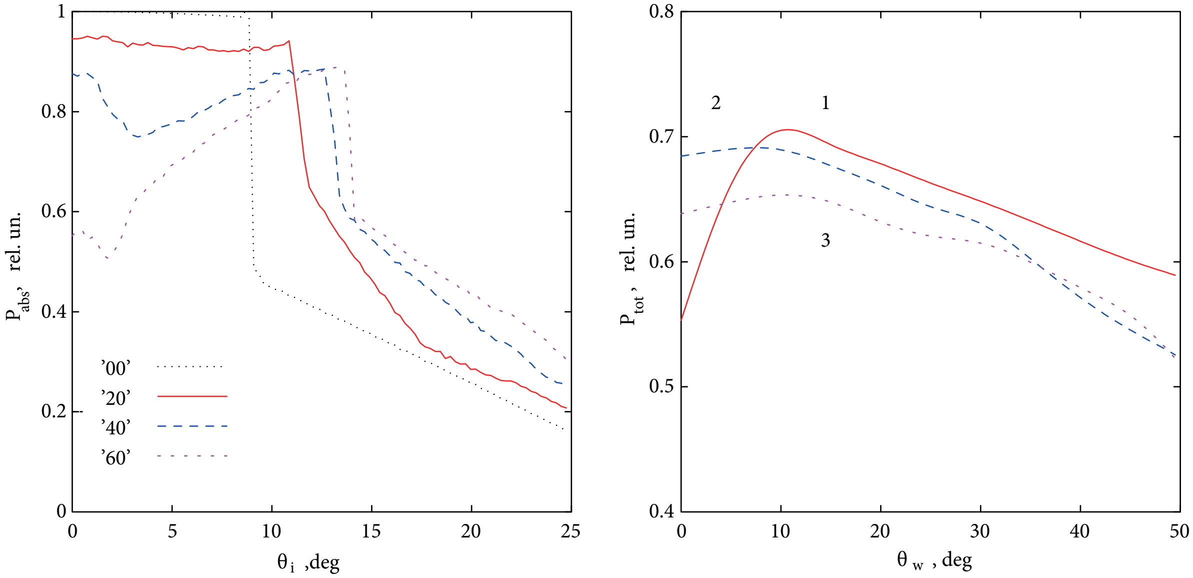

Figure 3. (a) Absorption power as a function of the incidence angle θ_i at various tilts θ_w of absorber wings (0, 20, 40, and 60 degrees) and (b) total power absorbed in a CPC as a function of tilt θ_w of absorber wings when integrated over the range of incidence angles θ_i due to daily variation of illumination conditions in a typical case of nontracking CPC operation (a CPC placed at the latitude of 40° and tilted towards the south by the angle of 7°, 12°, and 17° with respect to zenith on the days of the summer solstice, curves 1, 2, and 3, respectively).

Figure 3a shows that, in the case of a V-shaped absorber, the actual acceptance half-angle θ_a increases with increasing the tilts of absorber wings (the conventional angle θ is the value of θ_a obtained at the planar absorber). In addition, there is no complete cut-off of absorption when the light incidence angle exceeds the acceptance half-angle θ_a, which could be a useful feature for capturing the diffused component of light coming from the sky. Moreover, it is clear that making the tilt angles of about 10 to 20 degrees increases the total amount of power absorbed in the entire range of incidence angles with no significant hampering of absorption at the angles below the acceptance half-angle θ_a.

A more rigorous estimate of the optimal tilt of absorber wings is found through computing the total power captured by the absorber when integrated through the range of incidence angles due to varying illumination conditions. We assume that the nontracking CPC is west-east aligned, placed at the latitude of $\phi = 40°$, tilted towards the south by the angle of θ_{CPC} in the range of $7°$ to $17°$ with respect to the zenith, and illuminated by direct sunlight with typical daily variation of sun elevation and azimuth on the days of the summer solstice (we account for the angular-dependent air-mass effect on direct sunlight, though we neglect the diffused light component). The results are shown in Figure 3b where the optimal value of θ_w of about 10 degrees is confirmed. The estimate of this kind is approximate, since it is sensitive to the operation conditions, depends on the CPC design, and uses only the optical part of modeling. The account of thermal processes may alter the optimal value of θ_w, though the difference is not expected to be significant as compared to the effects due to other factors.

4. Conclusions

We consider computer simulation and optimization of compound parabolic concentrators for solar heat collectors. The approach that accounts for both the optical and thermal optimization of CPC collectors is discussed. Of particular interest is the collector of the enclosed design that has the top dielectric window and the light absorber suspended inside the structure so that the absorber is surrounded by mirrors on both sides and below with no thermal contact with the outer parts.

We present our developments in ray-tracing simulations of CPC collectors and show our results for the optical part of modeling of a typical trough-like CPC structure. A model CPC cell of medium collection efficiency $K \sim 4$ is considered, which is suitable for practical implementation as a nontracking system with seasonal repositioning of the collector.

We identify additional mechanisms of selective absorption in the solar collectors, which are complementary to conventional spectral selectivity of absorbers. One of them is the angular (spatial) selectivity, which is based on the difference in the angular dependence of absorption (emission) of infrared and visible light radiation, respectively. Another mechanism is the selectivity in time, which means an optimal dynamic scheduling of heat removal from the collector and further storage in multiple temperature stages depending on the variations in the solar radiation conditions.

We also consider the effect of different shapes of absorbers in the trough-like CPC collectors and present our ray-tracing results for a CPC with a V-shaped absorber. A range of optimal values of the apex angle of a V-shaped absorber is proposed for a particular kind of CPC collector as based on the optical part of modeling.

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