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Two non-tracking solar collectors: Design criteria and performance analysis

Wattana Ratismith [a], Anusorn Inthongkhum [a], John Briggs [a,b,*]

[a] Energy Research Institute, Chulalongkorn University, 10330 Bangkok, Thailand
[b] Theoretical Quantum Dynamics, Institute of Physics, Albert-Ludwigs Universität Freiburg, Germany

HIGHLIGHTS

- A collector module designed to capture solar radiation efficiently is proposed.
- Two different compound parabolic trough designs are examined and tested.
- A novel design with a flat base trough and vertical absorber operates efficiently in direct and diffuse sunlight.

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ABSTRACT

We propose fixed (non-tracking) configurations of solar light collector modules which are designed to operate efficiently throughout the day, i.e. for varying incident angles of direct sunlight, and in conditions of diffuse solar irradiation. We present two trough designs of compound parabolic collector (CPC) type. One, a more conventional double-parabolic trough, has the absorber plate perpendicular to the vertical axis of the trough cross-section. The other, of a new flat-base shape, has the absorber plate parallel. The collectors have two novel features appropriate to non-tracking. The first is a smoothing of the power output over the day by the simple expedient of arranging three troughs tilted at different angles. The second is the original design of the flat-base trough allowing optimal interception of the caustic surfaces of this non-focussing device. By ray-tracing analysis of the different trough shapes and absorber plate orientation, we emphasise the design criteria for achievement of a high intercept factor throughout the day without tracking and demonstrate the superiority of the flat-base collector over the double-parabolic design. In test experiments we show that the high temperatures (≈180 °C) necessary for some industrial process heat applications can be achieved. Also test results of the efficiency of the proposed systems are presented which indicate that the flat-base trough with vertical absorber plate is superior to the double-parabolic trough with horizontal absorber plate.

1. Introduction

As is well known, a conventional solar energy collector, consisting of a parabolic trough with an evacuated tube containing the absorber running its length at the focal point, is required to track the sun to achieve high efficiency [1–5]. In addition the focussing requirement renders it inefficient in diffuse sunlight. Such tracking systems are cost-intensive and unsuitable for easy use, for example in isolated environments. They are also inefficient in tropical climatic conditions such as pertain in Thailand where there is ample sunlight but a large percentage (up to ~60%) of which is diffuse, especially in the rainy season. The goal of this research is to overcome these difficulties by the design of a non-tracking configuration of non-focussing solar collectors which shows good efficiency throughout the whole daylight period under both direct and diffuse irradiation. We show that the salient feature in the design of these solar collectors is the use of a trough which utilises the non-focussing advantages of non-parabolic shapes in achieving high acceptance angle, high intercept factor and high concentration of diffuse sunlight [6–16]. Secondly we show that, in order to smooth the output power throughout the day, it is advantageous to use a three-trough collector where each trough is oriented to face the sun when it is at a different angle. It is these two features that enables this solar collector to receive sufficient sunlight at every angle and mitigates the power loss caused by not tracking the sun's position throughout the day.

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[*] Corresponding author at: Energy Research Institute, Chulalongkorn University, 10330 Bangkok, Thailand. Tel.: +49 07612035722; fax: +49 07612035748.
E-mail address: briggs@physik.uni-freiburg.de (J. Briggs).

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The advantage of the present design is that there are no moving parts in the system, and it is uncomplicated to install and easy to use. This collector yields temperatures of more than 100 °C and therefore has the possibility for high temperature process heat applications such as in domestic or industrial heating, cooking, drying or cooling processes. These results are part of an ongoing programme to design non-tracking solar collectors and our previous results are reported in Refs. [6,7].

The plan of the paper is as follows. In Section 2.1 we consider the advantages to be gained by a three-trough arrangement where the outer troughs are tilted, as compared to an arrangement where all troughs are vertical. We examine the variation of the power received by the absorber from the sun during the course of the day as a function of the tilt angle and the acceptance angle of a single trough.

In Sections 2.2 and 2.3 we discuss the choice of the shape of the collector troughs and by means of ray-tracing calculations illustrate the design performance in the collection of direct and diffuse sunlight under various angles of irradiation. Then we present two alternative designs of compound parabolic concentrator (CPC), one, a more conventional design is similar to those proposed in Refs. [17–19]. This design has a ridge running along the bottom of the trough long axis resulting from fusing two partial parabolas and has the flat absorber plate perpendicular to the vertical axis of the trough cross-section (Section 2.2). The second, a novel design, has a flat bottomed trough and the absorber plate is oriented parallel to the vertical axis of the trough cross-section (Section 2.3). We show that in both cases high intercept factors are obtained but, perhaps rather unexpectedly in that little direct radiation is absorbed, the flat-base design with parallel absorber orientation is superior. This is due to the achievement of an acceptance angle in excess of 60° and a large intercept factor throughout most of the day.

In Section 3 we describe experiments performed to test the temperatures achieved and the efficiency of operation of the two different CPC designs. Section 4 contains the conclusions to be drawn from this study.

2. The design of the trough collector module

2.1. Acceptance angle and tilt angle

In the following we consider, as experimentally determined in Bangkok, that the power flux for direct sunlight is very nearly constant over the time period 8 a.m. to 4 p.m.. Then the consequence of tilting the outer trough vertical axis by angles $\pm\alpha$ away from the vertical depends strongly upon the acceptance half-angle θ_0 of an individual trough in the three trough arrangement. Clearly, were the acceptance angle small and all troughs vertical ($\alpha = 0$), without any tracking, power would be collected only during a small part of the day. Tilting the two outer troughs would not lead to an increase in total power but would lead to each trough having maximum acceptance before, at, and after noon respectively. Hence one sees the main advantage of tilting is to smooth the power output of the device during the daylight hours.This is illustrated in the simulation shown in Fig. 1. Here we assume that the direct solar irradiation at angle θ is constant at $G = 800\ \mathrm{W/m^2}$, corresponding to a clear sunny day in Bangkok. Then we plot the total power W entering the collector and transmitted to the absorber in $\mathrm{W/m^2}$ as a function of the angle θ from the vertical. The total power is given by the sum of three terms for the left (L), centre (C) and right (R) troughs. The intercept factor $I(\theta)$, defined, for the moment, as the percentage of flux entering a trough at a given angle of incidence which is intercepted by the absorber, is taken to have a Gaussian distribution whose width is the acceptance half-angle θ_0. The Gaussian shape is a good fit to measurements of the intercept factor we have made under direct irradiation conditions. The expression for absorbed power then reads,

$$W(\theta,\alpha) = G\left[e^{-\frac{(\theta+\alpha)^2}{\theta_0^2}}\,\Theta(90-(\theta+\alpha))\cos(\theta+\alpha) + e^{-\frac{\theta^2}{\theta_0^2}}\cos(\theta) + e^{-\frac{(\theta-\alpha)^2}{\theta_0^2}}\cos(\theta-\alpha)\right] \tag{1}$$

where the step function Θ serves to cut off the contribution of trough L when the angle of incidence is such that no light enters this trough. This function is plotted in Fig. 1a and one sees that, if the acceptance angle is small, the tilting does lead to a broader time distribution of solar power collection without significant reduction in the total.

At the other extreme, if θ_0 were unrealistically equal to the maximum value of 90° then clearly the orientation of the troughs is immaterial and there is no effect of tilting. In Fig. 1b we show an example for realistically large acceptance half-angle of 40°. Then one sees that in this case tilting of the troughs leads to more absorbed power only for large angles of incidence when non-tilted troughs would have ceased accepting sunlight. In summary, if the acceptance angle is modest, tilting the troughs leads to a smoothing of the output power but for large acceptance angle, where the need for tracking is practically eliminated, the advantage from tilting the troughs is marginal. Note that here, in order to concentrate on the effect of tilting, we have assumed that all rays entering the absorber deliver the same power. That is we have made no correction for losses due to reflection at the trough surface, transmission through the glass cover of the absorber or less than 100% absorber efficiency. These effects are considered below.

2.2. The Double-Parabolic Trough (DPT)

In the experiment we use exclusively the commercially-available SUNDA (SEID01) vacuum tubes of length 2.1 m with a planar absorber plate of width 9.0 cm. Hence, in our design of the trough and in all ray-tracing cross-section diagrams presented below, this width determines the length scale. The aim is to design a trough in which this flat-plate absorber is optimally irradiated throughout the day, which implies achieving large acceptance angle and intercept factor. The first shape chosen to optimise the collection of direct and diffuse light is composed of segments of two identical parabolic troughs whose shape in a frame with origin at the respective minima is simply $y = ax^2$, see Fig. 2a. The compound trough is assembled by first truncating the inner wall of each of two parabolae at fixed points $\pm x_0$ and then fusing them at the cut point whilst at the same time orienting them inwards at an angle of 15°, see Fig. 2b [6,7]. This forms a single trough with a double minimum and a central peak running the length of the trough. The overall physical size of the trough is then determined by the placement of the absorber tube of fixed size. The vertical height can be chosen arbitrarily by truncating the trough wall to achieve the desired compromise between acceptance angle and concentration ratio, depending upon the size and disposition of the absorber.

Clearly there is a wide choice of truncation point and tilt angle of the two halves of the single trough. In principle one could perform an optimisation calculation to find the values giving maximum light collection efficiency. In practice it is simpler to vary the parameters and by visual inspection of the pattern of light reflection obtained from a ray-tracing diagram to determine the favourable configuration. This is the approach adopted here. To this end we have written a ray-tracing computer program accommodating arbitrary angle of incidence of light rays whose multiple