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Concentrating sunlight with an immobile primary mirror and immobile receiver: Ray-tracing results

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Abstract

Using a combination of custom computer code and commercially available ray-tracing software, we explore variations of concentrator geometries where sunlight is first incident onto a stationary primary mirror of circular cross section. The reflected radiation is incident onto a smaller, secondary moveable mirror, which focuses the radiation onto a stationary target. Simulations for this trough geometry show peak concentrations of 38 solar equivalents.

Keywords: Solar energy; Solar concentrator; Ray tracing; Trough concentrator; Fixed focus

1. Introduction

Large solar concentration devices have traditionally consisted of a parabolic primary mirror, which focuses radiation onto a target, such as a heat collecting element (HCE) or photovoltaic cell (PV). In order to keep the target at the focus of the primary mirror, the entire mirror must rotate about either one axis (for trough systems), or two axes (for dish systems).

The need to rotate the assembly constitutes a considerable amount of the capital cost for modern Solar Thermal Electric (STE) facilities. The mirrors and HCE are often made of glass and must be delicately held in place with a high degree of angular tolerance, while hot (and possibly pressurized) fluids circulate in the HCE and through piping that must pivot as the drive mechanism tracks the sun. A recent NREL (National Renewable Energy Laboratory, Golden, Colorado) study (Stoddard et al., 2006) indicates that 60% of the cost of an STE facility is the solar field. Half the cost of this solar field including pylons, metal support structure, mirrors, drive system and piping interconnects may be due to the need to track the large parabolic mirrors (Sargent and Lundy LLC Consulting Group, 2003).

Some innovations reduce the extent of hardware necessary to track the sun and most are described in a single text (Winter et al., 1991). Many innovations include an immobile primary mirror of circular cross section that is either a trough or dish (i.e. sphere, or bowl), and a mobile target that tracks the area of concentrated radiation (Rabl, 1985). The most famous spherical concentrator is the radio telescope at Arecibo, where incident radio wave radiation is reflected from an immobile spherical bowl about 300 m across onto a movable secondary concentrator and receiver allowing observations of up to 20° from the zenith. Similarly, a trough of circular cross section can be used to concentrate radiation onto a moveable linear secondary target. Whether a trough or dish, the primary mirror has a circular cross section of radius *R*, rather than a parabola in order to avoid the aberration that increases with radiation of increased off axis incidence (Fig. 1a). A mirror of circular

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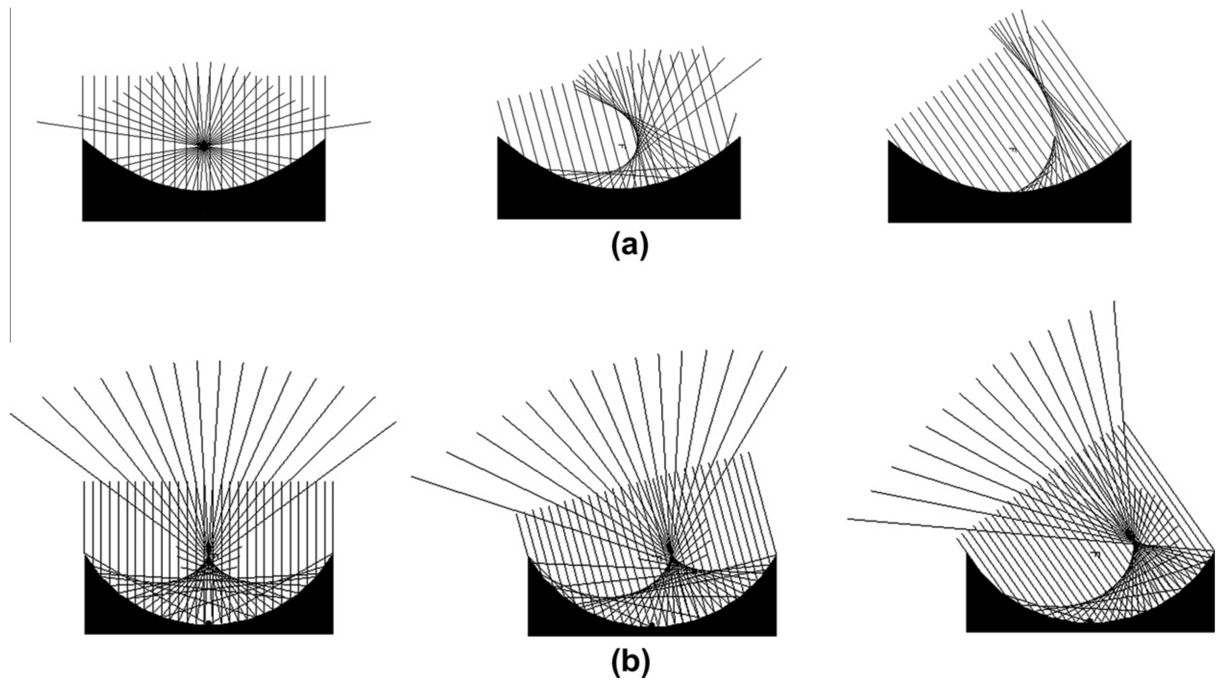

Fig. 1. Incident sunlight (shown as parallel lines) on (a) a parabolic mirror, and (b) a circular mirror, at the angles indicated. The parabolic mirror focuses only the axially incident radiation to a point. Radiation reflected from the circular mirror is not focused to a point. However, at all incident angles, the area of focused radiation has the same mathematical form albeit in a different place.

cross section produces a consistent spherical aberration for all incident angles (Fig. 1b). Radiation that is near perpendicular to the circular surface (incident angle of 0°) is reflected through a point $R/2$ from the center of curvature. Radiation at higher incident angles is focused to points at larger radii (closer to the surface of the circular mirror), focusing on the mirror surface itself for incident angles of 60°. Incident angles greater than 60° result in multiple reflections. For a "solar bowl collector" all incident radiation is ultimately reflected onto a movable target kept parallel to the incident radiation along the radius vector of the bowl, extending from the mirror surface to $R/2$ (E1-Refaie, 1987; O'Hair et al., 1986, 1987). Another trough geometry makes use of an immobile faceted (Fresnel) primary mirror that focuses incident radiation onto a line on a cylindrical surface, where the reflected radiation is absorbed by a mobile line absorber (Russel and Deplomb, 1975).

All the above innovations lower the mass that needs to be moved in solar tracking. However, these innovations may also result in the following problems: additional complication in the tracking mechanism, as well as reduction of solar concentration or collection efficiency. We propose a trough design that allows both the primary mirror as well as the absorber to be stationary, using a smaller, moving secondary mirror to redirect the radiation reflected off the stationary primary mirror. Consistent with the above alternative concentrator designs, our design greatly reduces the mass that needs to track. This gain comes at the expense of collection efficiency, concentration, and simplicity of tracking. While this ray-tracing study presently satisfies academic interest, future improvements may enable applications in solar energy or other fields.

The design we propose is similar to that of a Gregorian telescope (Fig. 2). In such an optical system, a large primary concave mirror directs radiation onto a smaller secondary concave mirror, which serves to correct for spherical aberration and redirect the radiation back toward the target past the primary mirror. Such a system has been studied before as a way to achieve high solar flux concentrations (Leutz and Ries, 2005). However, in this previous work

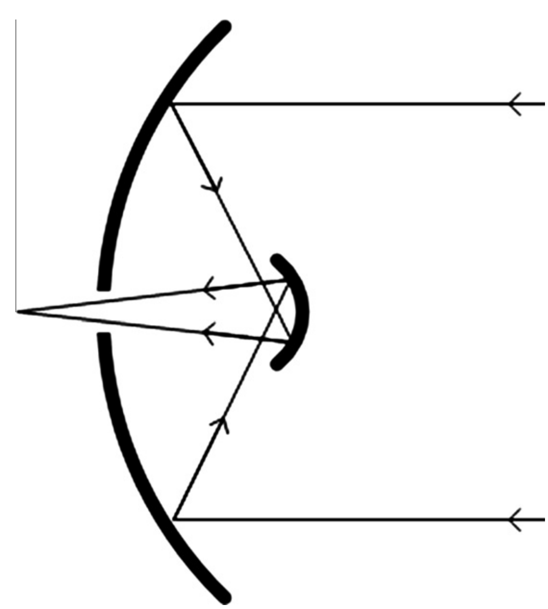

Fig. 2. Diagram of a Gregorian telescope.