Optics & Laser Technology 54 (2013) 274–283

Contents lists available at ScienceDirect

Optics & Laser Technology

journal homepage: www.elsevier.com/locate/optlastec

Transmissive, non-imaging Fresnel types of reflective radiation concentrators revisited

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ARTICLE INFO

Article history:
Received 22 January 2013
Received in revised form
18 April 2013
Accepted 7 May 2013
Available online 2 July 2013

Keywords:
concentrator
solar
photovoltaic

ABSTRACT

The principles of operation are described for a broadband transmissive radiation concentrator system comprised of reflective nested frustoconical shells with a common axis. The theory for such a system is first developed and then extended to that of a reflective spiral geometry, a system which is more readily realised in a practical device. Proof of principle of such a reflective Fresnel spiral scheme is demonstrated experimentally by two distinctive types of design for solar concentrators with promising radiation collection efficiency.

1. Introduction

Transmissive axial radiation concentration based upon reflection methods can give be achieved over a very wide spectral range since the problems of selective wavelength absorption and dispersion of dielectric lenses are avoided. Moreover there is no chromatic aberration. In principle, reflection methods can cover the wavelength range from the extreme ultra-violet, through the visible, to far infrared wavelengths, and using glancing angle techniques can also be used for X-ray concentration.

Many methods have been proposed for reflective concentrators systems in transmission. Of these many have found a practical realization and have been widely used. Here, only three dimensional types are considered and the following short list of devices indicates the diversity of a selection of the systems already studied. These include those based on conic reflector sections (e.g. paraboloidal, ellipsoidal, hyperboloidal in various shell forms, sometimes in combination with another optic); compound parabolic reflectors and their variants [1]; a single or multiple reflection frustoconical shell [2,3] or truncated pyramid [4]; multicellular types: microchannel plates, hollow glass fibres or fibre bundles [5]; multiple reflection multi-foliate single or double-sided reflectors [6]; Fresnel types in the form of nested shells of frustocones, truncated cylinders [7,8] or parabolas [9,10]. Alternatively, a wound-up spiral ribbon in 'cylindrical' or 'conical' forms has been used [7,11]. Many of these have been developed for the X-ray and optical spectral regions, but somewhat independently. Most but not all of these methods, as noted, are based on a *single* reflection. Two important practical exceptions are the double reflection method of Kirkpatrick-Baez which uses two orthogonal parabolic surfaces in series for parallel-to-point focusing [12], or the double reflection Wolter-I configuration, in the form of nested confocal paraboloid-hyperboloid wafer thin shells [13,14]. Other multiple reflection schemes are the tapered monocapillary and polycapillary glass types [15]. All of these last mentioned types have been used for the concentration of X-rays.

This paper first sets out to explore the theoretical essentials of a *non-imaging* reflective Fresnel type concentrator for the optical region to give an insight into the relevant experimental parameters for a successful yet simple method of construction. It should be noted at this point that the notion of a wound-up spiral type of Fresnel concentrator had been studied before and a detailed theory developed for it [11]. The novel aspect of that particular patented design was that it started as a spiral cut out of a flat sheet of reflective material following a computer-generated locus. When wound up about an axis in common with that of a collimated radiation source, a type of Fresnel concentrating spiral structure was obtained. Two forms of related spiral devices were proposed, each with their related supporting theory. The first had a shallow dish-like profile and the second a 'frustoconical' shell form of spiral.

In the design of the first device, the inner edge of the spiral ribbon lay on a radial plane orthogonal to the direction of the incoming collimated radiation whereas the outer edge of the spiral started flat on the wound-up spiral's axis and thereafter acquired a small angle with respect to that plane which increased with turning angle. The device constructed in this way was described as having a positive focal length, i.e. one in which the focal point

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http://dx.doi.org/10.1016/j.optlastec.2013.05.013

was on the side of the incoming radiation. Variations of this basic design not considered here were also proposed. A tested device of this type was reported to have a concentration of 500 suns but without any details of how this was achieved.

The second type of concentrator proposed in Ref. [11] had a negative focal length and so had the property of concentrating radiation in transmission. Here, a cut-out of a computer-generated spiral in flat sheet form took the shape of a reflecting ribbon whose width and radius of curvature gradually expanded as the spiral's rotation angle increased. Here, the outermost portion of the spiral (which took the appearance of a trumpet-shaped flare in cross section) was curled up into a wound-up spiral concentrator where the flared outer end part of the ‘frustoconical’ shell spiral close to the concentrator's hub started with an angle of inclination of about 5° relative to its axis. Successive spiral turns of gradually increasing radius of curvature, and decreasing spiral ribbon width took on increasingly larger angles out to about 28° according to a sketch in Ref. [11]. In this case the direction of winding was opposite to that for the previous positive focal length wound-up spiral. Here, the inner edge of the spiral originally in flat sheet form now lay on a radial plane of the full area of the concentrator's radiation exit. The external profile of the concentrator was similar to that of an upturned kitchen bowl where the collimated incoming radiation rays entered the curved surface from above and left after reflection from the multiple turns of the tilted spiral ribbon to a focal point in common below. With this arrangement the outer convergence angle of the concentrated rays was as much as 112°. No details of actual construction or experimental results are known for this second design.

This paper revisits the topic of radiation concentration based on a Fresnel type of wound-up spiral reflector and presents a much simpler albeit less exact approach to the underlying theory than presented in Ref. [11] for a transmitting spiral concentrator with a negative focal length, as just described. In this new presentation the basic theory is first developed for a nested frustoconical shell type of Fresnel concentrator which is subsequently modified to give a fair theoretical basis of a ‘frustoconical’ wound-up Fresnel spiral. Based on this theoretical background, the design and construction of experimental systems using the ‘frustoconical’ forms of two basic types Fresnel spiral are presented. These have demonstrated practical solar radiation collecting efficiencies, even in prototype form, in excess of 140 suns averaged over the full cross sectional area of the focal volume with a significantly higher concentration in the centre. The possibility of realizing several times this value in future devices following the same methodology is discussed.

2. Basic principles of operation

The radiation concentrator scheme first considered in this paper is based on a set of coaxially nested frustoconical shells reflecting incoming collimated or near-collimated radiation into a small focal volume. Sets of surfaces such as these can be produced in several ways with differing degrees of complexity. For example, thin frustoconical shells may be produced by electroforming using a finely machined and polished former. Another possible method is to stamp out reflectors individually from a flat reflective sheet. A more practical and less costly technique is to use ring sectors of appropriate lengths cut from a circular ring prepared from a thin flat reflective sheet of metal. The ends of the sectors are then joined to form a nested set of thin frustoconical shells, each with the required radius and angle of inclination relative to their common axis, henceforth described as the x-axis.

The basic parameters of this last mentioned method are calculated as follows. Consider a ring of width d cut from a flat sheet of highly reflecting material of inner radius R'' as sketched in Fig. 1(a). The ratio, S, of outer to inner ring circumferential segment of any length is given by

$$S = (R'' + d)/R'' \quad (1)$$

When the reflector section is curled into the nth frustoconical shell inclined at an angle γ_n to the x-axis as shown in section in Fig. 1(b), the ratio of outer to inner radius R_n is given by

$$S = (R_n + d\sin\gamma_n)/R_n \quad (2)$$

Combining Eqs. (1) and (2) gives

$$\sin\gamma_n = R_n/R'' \quad (3)$$

Fig. 2 shows in cross section the upper radial part of a set of nested frustoconical shells with their trailing edges set on a radial line normal to the x-axis. These edges are shown as equispaced but with exaggerated separations for the purpose of illustration. The ray reflected from the trailing edge of the uppermost reflector intersects with the x-axis at a distance x_n from the intersection of the radial line and the x-axis given by

$$x_n = R_n/\tan 2\gamma_n \quad (4)$$

where R_n is the inner radius of the trailing edge of the nth frustoconical shell, inclined at an angle γ_n. For small values of γ

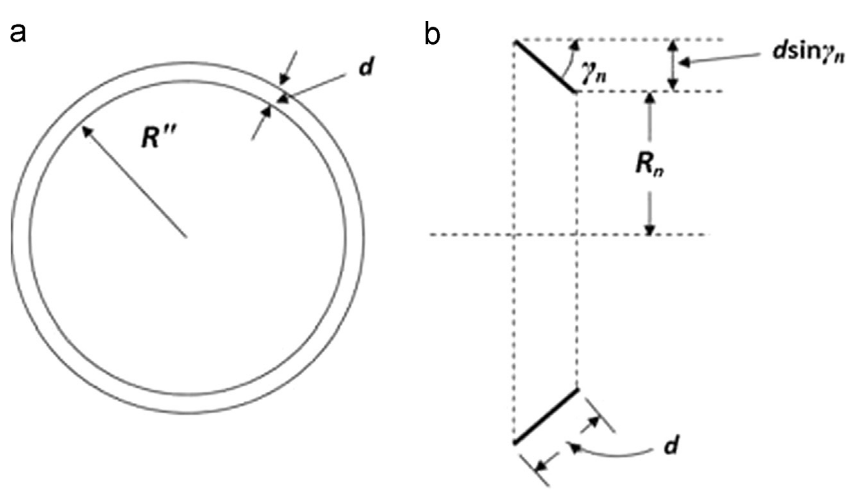

Fig. 1. (a) Schematic diagram showing a large ring cut out of a flat sheet of reflecting material; (b) An enlarged segment of the ring shown in (a) to form a single shell of a reflective frustocone. Sketches (a) and (b) are only illustrative and not to the same scale.