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Etendue-matched two-stage concentrators with multiple receivers

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Abstract

A possible way to concentrate sun light is by using a Fresnel reflector: a large number of small mirrors (called heliostats) that mimic the behavior of a large concentrator, replacing it. These heliostats can move to track the sun, keeping its light concentrated onto the receiver. Fresnel concentrators, however, may have important losses. If the heliostats are spaced from each other, some light will miss them and be lost. If the heliostats are close to each other, they will block part of each other's reflected light, also producing losses. One possible way to minimize these losses is to intersect two focusing Fresnel concentrators forming a Compact Linear Fresnel Reflector – CLFR. Although improving on a simple focusing Fresnel concentrator, these optics are still not optimal. Here new geometries for Fresnel reflectors are explored, minimizing their losses and increasing their concentration. This is achieved by changing the overall shape of the primary, making it a wave-shaped trough surface and/or by allowing for a variable size and shape of the heliostats as a function of the position in the heliostat field. These new Fresnel concentrators may also be combined with secondaries significantly improving their total concentration, which now approaches the theoretical maximum.

Keywords: Fresnel concentrator; Heliostat; Nonimaging; Etendue-matched; CLFR

1. Introduction

When using high-efficiency solar cells or thermodynamic cycles (heat engines), some degree of concentration of sunlight is needed. In the first case, high efficiency cells are expensive and concentrating optics potentially much cheaper. In the second case, high temperatures can only be efficiently achieved through concentration and low thermal losses, those of an absorber proportionally smaller than the aperture intersecting the solar radiation. These concentrators typically require some tracking capacity of the sun's apparent daily motion.

Sunlight is concentrated using either focusing optics, nonimaging optics or a combination of both (Chaves, 2008). One possibility is to use Fresnel reflectors (Ortega et al., 2006; Sanchez and Romero, 2006; Quaschning, 2003). An improvement over the simple Fresnel primary is to intersect two flat heliostat fields in an arrangement known as CLFR (Compact Linear Fresnel Reflector) (Mills and Morrison, 2000). In this arrangement, instead of a single receiver there are several receivers. The heliostats closer to a first receiver redirect the light to it. Those further apart, alternatively redirect the light to the first receiver and to a second receiver. This creates a W shaped heliostat field in the areas further apart from the receivers where the odd heliostats reflect light to one receiver, while the even heliostats reflect light to the other receiver. This approach, however, does not match the etendue of the incoming radiation with that reflected to the receivers and, therefore, there will always be either some blocking of light or areas of the heliostat field not fully illuminated when seen from the receivers. This is a fundamental

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limitation of these optics and is independent of the size or shape of the heliostats (which are all flat and the same size in the CLFR configuration).

New primaries are needed to solve the etendue-mismatch problem between the etendue of the light received by the primary and the etendue the primary should ideally redirect towards the receivers. Secondary optics are also needed to further boost the concentration to values close to the theoretical limit.

This paper is about two different ways of improving the primary: changing its overall shape and changing the size and shape of its heliostats (Chaves and Collares-Pereira, xxxx). The heliostats are now placed on a wave-shaped trough surface and their size and shape is a function of the position in the heliostat field. The heliostats, however, constitute a discontinuous primary and strategies to design a continuous secondary for these optics are also presented.

The paper also presents a concept for reducing convection losses at a thermal receiver. These include transparent covers and specially shaped mirrors.

2. Etendue balance and etendue-conserving curves for Fresnel reflectors

Concentrating collimated light to a receiver (focus) may be achieved by using a parabolic mirror. In the case of incident light with a small angular aperture, all the incoming rays are redirected towards the receiver while conserving etendue.

An alternative way to concentrate light to a receiver is by means of a Fresnel concentrator, which is composed of a large number of small mirrors, all redirecting the light to a receiver (focus) **F**. A theoretical limit case may be considered where this concentrator has an infinite number of infinitely small flat mirrors. These are represented in Fig. 1a as a horizontal flat line C_F. Fig. 1b shows a few of those infinitesimal Fresnel mirrors at point **P**.

The aperture available at point **P** is dl and the etendue is $dU_1 = 2dl \sin\theta$ for the incoming and $dU_2 = 2dl \sin\theta \cos\theta$ for the reflected radiation. The projection of dl in direction φ is $da = dl \cos\varphi$. It can be seen that etendue is not conserved since dU_2 is lower than dU_1 by a factor of $\cos\varphi$. Accordingly, in Fig. 1b) the mirror to the left blocks the rays between r_1 and r_2 (this blocking would not occur if line C_F was shaped as a parabola).

In dealing with the light that cannot be coupled in direction φ (blocked light) because etendue conservation does not allow it, there are two options: either to loose it or to reflect it somewhere else. Fig. 2 shows another situation in which a point **P** receives light from the vertical and reflects it to two receivers $\mathbf{R}_1$ and $\mathbf{R}_2$.

Again, at this point **P** we have a small aperture dl for the incoming and exiting light, for which the etendue balance can be calculated. The normal **n** to dl is tilted by an angle α to the vertical and the etendue of the incoming radiation in the vertical direction is then given by $dU_0 = 2dl \cos\alpha \sin\theta$. Angle α is a parameter that will be determined below for

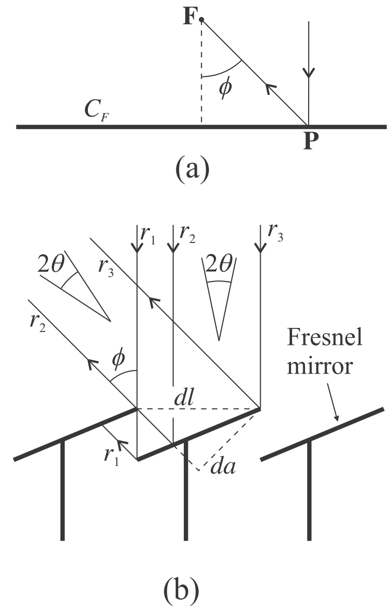

Fig. 1. For a set of Fresnel mirrors on a plane, the etendue of the incoming and reflected radiation to the receiver are not equal because of blocking from adjacent mirrors.

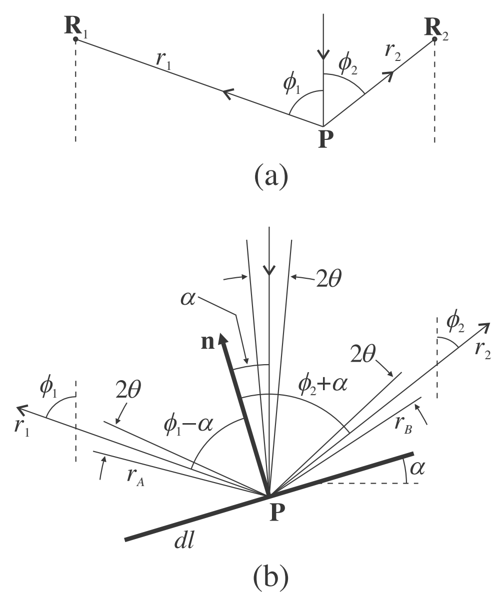

Fig. 2. (a) Incoming light can be reflected to two receivers and (b) etendue balance for a small length dl at point **P**, for the case in which the light is reflected to two receivers.

each point **P**. The etendues of the light reflected to receivers $\mathbf{R}_1$ and $\mathbf{R}_2$ are, respectively, $dU_1 = 2dl \cos(\varphi_1 - \alpha) \sin\theta$ and $dU_2 = 2dl \cos(\varphi_2 + \alpha) \sin\theta$. Angles φ_1 and φ_2 are those the bisectors of the reflected light beams make to the vertical. For a given angle α, conservation of etendue at point **P** can then be written as:

$$dU_0 = dU_1 + dU_2 \Rightarrow \cos(\phi_1 - \alpha) + \cos(\phi_2 + \alpha) = \cos\alpha \tag{1}$$