DEVELOPMENTS AND DESIGNS OF SOLAR ENGINEERING FRESNEL LENSES

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ABSTRACT. This paper deals with the suitability of Fresnel lenses of imaging and nonimaging designs for solar energy concentration. The paper's scope is the review of long known, and recently developed Fresnel lenses, and the analyes of their characteristics for utilization as solar concentrators, putting an emphasis on a lens designed by the authors. Nonimaging optics are presented as offering the possibilities needed for a breakthrough of Fresnel lenses in commercial solar energy concentration, both in photovoltaic and thermal power conversion.

NOTE. Rather than delivering an exhaustive list of papers whose authors have contributed to the advances in the field, we have decided to focus on dominant designs, space permitting. A comprehensive reference list will be sent upon request.

1. INTRODUCTION

Fresnel lenses are used as solar concentrators since they offer high optical efficiency along with minimal weight and low cost. Applications that demand medium and high concentration ratios (> 20), such as monocrystalline photovoltaic generation of electricity, are often equipped with imaging Fresnel lenses. Accurate tracking has to be employed to keep the focus of the lens in place on the receiver. Fresnel lenses are to find a much wider field of utilization, if their optics are adjusted to the requirements of a seemingly moving sun.

Nonimaging optics (Welford, Winston 1989) offer the possiblity to design Fresnel lenses as stationary concentrators with low concentration ratios. For medium flux applications, nonimaging Fresnel lenses are forgiving errors due to installation, low precision tracking, and the finite size of the sun. Not photographic imaging counts, but the homogeneous illumination of a receiver. Two pairs if acceptance half angles are defined, θ in the cross–sectional plane, and ψ perpendicularly to it. They are spanning a part of the hemisphere, thus opening a window through which the concentrator 'sees' the sun. Fresnel lenses of nonimaging design are usually (but not necessarily) of convex shape, while their imaging counterparts are most often flat.

2. FRESNEL LENS DESIGNS FOR THE COLLECTION OF SOLAR ENERGY

Initially, most Fresnel lenses propositioned for solar energy use had not been designed for collection of solar rays. These lenses were imaging devices subject to strong focal forshortening, once the solar rays were no longer entering at an angle normal to the collectors surface. Imaging lenses are designed starting with their focal length. The design principle is trying to eliminate aberrations in order to accomplish a most exact focus. While a neat focal point is characteristic to very high concentration ratios (defined as ratio of aperture, or lens area, to receiver area), imaging is not necessary for collecting solar energy. If not for some cases where high concentration is needed, why should one trouble oneself with accurate tracking of the sun due to the use of imaging lenses under the appearently moving sun?

Table 1 gives an overview of recently achieved developments in the design of Fresnel lenses suitable for solar energy collection. The designs listed are not evaluated but can be described by certain characteristics. Fresnel lenses can be designed according to principles and assumptions which are listed below. The number of designs in Tab. 1 is not exhaustive but common trends are emerging.

Table 1: Major developments in Fresnel lenses suitable for solar applications.

Year	Researcher(s)	Application	Nonimaging optics	Solution numerical only	Cross–sectional angle θ	Perpendicular angle ψ	Minimum deviation prism	Edge ray principle	Fashionable design	Thin lens, $f >> d$	Prism size, $\Delta x \rightarrow 0$	Flat lens
1822	Fresnel[1]	lighthouse	–	–	–	–	–	–	–	–	–	○
1951	Miller *et al.*	condensers	–	–	–	–	–	–	–	–	○	○
1973	Szulmayer	solar	–	–	–	–	–	–	–	–	○	○
1975	Nelson *et al.*	solar	–	–	–	–	–	–	–	–	○	○
1977	Collares–Pereira *et al.*[2]	solar	–	–	–	–	–	–	–	○	○	–
1978	O'Neill	solar	–	–	○	–	○	–	–	–	○	–
1979	Collares–Pereira	solar	○	○	○	–	–	○	–	○	○	–
1979	Kritchman *et al.*	solar	○	○	○	–	–	○	–	○	○	–
1981	Lorenzo, Luque	solar	○	○	○	–	–	○	–	○	○	–
1984	Tver'yanovich	solar	–	○	–	–	–	–	–	–	○	○
1997	Erismann[3]	infrared	–	○	–	–	–	–	○	–	○	–
1999	Leutz *et al.*	solar	○	○	○	○	○	○	–	–	○	–

[1]First aspherical lens, refer to Aničin *et al*, 1989; [2]refractive index $n \rightarrow \infty$, idea W. T. Welford; [3]aspherical lens in spherical shape.

Design principles

Nonimaging optics: The lens in question is designed according to the principles of nonimaging optics, which were discovered in the 1970's, and found well suited for solar energy applications.

Solution numerical only: The nature of the mathematics used in Fresnel lens design sometimes does not allow an analytical solution. If the number and extent of assumptions are to be reduced, numerical solutions may be called for. As this generally requires a large numer of iterations, computer based simulations are needed.

Cross–sectional angle θ: Any lens, whether of rotational symmetry (3D), or line focusing (2D) is designed with the help of a cross–sectional acceptance half angle which determines the part of the sky the lens may 'see'. Imaging lenses are generally designed focusing paraxial rays only, $\theta = 0$. However, the absorber, first, is larger than the focal *point*, and second, can be moved out of focus, in a way that some rays incident at an angle θ are collected.

Perpendicular angle ψ: The focal areas of line focusing, 2D–lenses (imaging or nonimaging) are sensitive to changes of the incidence angle not only in the cross–sectional, but also in perpendicular plane. The significance of this has often been overlooked when designing Fresnel lenses for solar applications, where 2D characteristics are desired.

Minimum deviation prism: Optical losses during refraction at a prism are least at the minimum deviation prism, where the angles of incident and exiting rays to the respective prism surface are equal.

Edge ray principle: This principle goes along with nonimaging design of Fresnel lenses. Light incident at maximum combinations of acceptance half angles is directed towards one end of the absorber. Fresnel lenses as a rule refract light incident from left of the optical axis of each prism towards the right side of the absorber, and vice versa.

Fashionable design: Solar energy applications, as well as manufacturing technologies usually require the outer side of the lens to be flat. Given this and the principle of minimum deviation prisms, an optimum convex shape of the Fresnel lens emerges from the simulation. Relaxing either principle, the design of lenses of other shapes is possible. 'Fashionable' could mean circular, for example.

Assumptions

Thin lens, $f >> d$: When the thickness of the lens d becomes small in comparison to its focal length f, the sine theorem can be applied during the simplified simulation of the lens. Furthermore the lens is often assumed to have no thickness at all at the thinnest point, $d = 0$. With this assumption, it becomes possible to set up an equation describing the refracted (but not relocated) rays emerging from a prism, in relation to prism center and absorber.

Prism size, $\Delta x \rightarrow 0$: The size of prisms in comparison to the absorber width is assumed to be small in all designs. Each prism is designed only once, but with some $\Delta x > 0$ extending from the design point, ideally in both directions. If that Δx becomes too large, the direction of the ray emerging from one of the extremes of the prism may not point to the absorber. In combination with the edge ray principle of nonimaging designs, extreme rays from extreme ends of the prism will miss the absorber. For imaging designs, any prism width greater than zero is influencing imaging quality, since the width of the ray emerging from the prism is always larger than the focal point, with width zero. In some imaging designs with very high optical quality requirements, one of the active prism surfaces if curved to account for this potential error, as was Fresnel's original center prism. Prisms cannot be made smaller than a multitude of wavelengths, if the rules of geometrical optics should hold accurate.

Flat lens: Fresnel lenses, in particular imaging Fresnel lenses are often assumed to be flat. This does not have to be the case, imaging lenses can be shaped, as nonimaging Fresnel lenses can be designed as flat lenses. Optimized nonimaging lenses with smooth outer surface must be shaped to allow for concentration of light incident from both the left and the right extremum given by the acceptance half angle(s).

Nonimaging Optics

Nonimaging optics were discovered for their use in solar energy with the discovery of the (reflective, not refractive) Compond Parabolic Concentrator (CPC) by Winston (1974), refined by Rabl (1976). A book named "The Optics of Nonimaging Concentrators" by Welford and Winston (1978), later enlarged as "High Collection Nonimaging Optics" (Welford and Winston, 1989), became the standard text for nonimaging applications in solar energy, and other fields. The linear CPC is designed starting with a cross-sectional acceptance half angle spanning part of the hemisphere, thus accepting a fraction of the sun's energy, collecting solar rays whenever the collector, enabled and restrained by the acceptance half angle, is able to 'see' the sun. The higher the concentration ratio, the smaller the acceptance half angle. The CPC's mirror walls are of parabolical shape. A nonimaging concentrator is called ideal when all light within the limits of the edge rays is refracted onto the absorber. Nonimaging Fresnel lenses approach, but do not reach the ideal due to blocking and unused tip losses inherent in the prisms' design, and the effects of refraction in the perpendicular plane.

It did not take long until the concept of nonimaging optics was applied to (refracting) Fresnel lenses. In the 1970's, both Kritchman *et al.* (1979a, 1979b, 1981, 1984), and Collares–Pereira *et al.* (1977, 1979) designed bifocal Fresnel lenses, which are essentially nonimaging devices. Both groups of designers intended to construct nonimaging lenses to enhance the ability of the lens to collect rays from a appearantly moving sun within a cross–sectional pair of acceptance half angles. O'Neil (1978) designed a focusing lens, but realized that his lens could compensate for tracking errors within narrow limits. Lorenzo and Luque followed 1981, and are followed by the work of Leutz *et al.*, which is probably the first nonimaging design of a Fresnel lens offering finite size prisms and a lens thick enough for manufacturing, taking into account the perpendicular acceptance half angle. These milestones of development have been listed in Tab. 1, to compare design principles and assumptions made.

3. IMAGING FRESNEL LENSES

Typical imaging (flat) Fresnel lenses are designed as focusing devices, i.e. the main parameter is the focal length of the lens. Flat nonimaging Fresnel lenses have not yet been published, although this would not be impossible (only if one surface has to remain smooth). As long as certain assumptions are made, focusing lenses can be solved analytically. Such assumptions include the (reasonable) definition of the lens as thin, meaning that its focal length f must be much greater than its thickness d, $f >> d$. Two papers were published in 1951 (Miller *et al.*, and Boettner, Barnett). The former group had designed and constructed Fresnel lenses for technical applications beginning in 1948, taking advantage of the new plastic materials. Their lens designs are of imaging type, and the losses at a Fresnel lens as well as the spectral behaviour of the prisms (Oshida, 1961) are already well understood.

Research has focused on the development of evaluation techniques for Fresnel lenses under solar radiation. Ray tracing has been applied to find whether an incident ray hits an absorber, or misses it (Nelson *et al.*, 1975). The forshortening of the lens' focus has destroyed many hopes to successfully use imaging Fresnel lenses as solar collectors. Tracking is an expensive option, and has only recently been developed to a stage of maturity. Harmon (1977), who evaluates mass–produced focusing Fresnel lenses for their applicability in photovoltaics, probably captures what most results of simple lens analyses indicate, when he describes the lens as being

> "...an inefficient concentrator with losses that begin at 20 per cent and rise to about 80 per cent as the focal distance decreases. However, the lens is capable and adequate for low concentration purposes with photovoltaic systems. The most attractive aspects of using this lens as a solar concentrator are its availability and its potential low cost."

Designs can become more complicated than the typical focusing lens outlined, when a cover, or a coating is involved, or when the lens sports grooves on both sides. In these cases, analytical solutions can no longer be offered, and numerical calculations are introduced. One reason why research has in the past often treated only the feasibility of existing focusing devices for solar energy applications might be the lack of computing power solving numerical problems for lenses with hundreds of prisms, which, done by hand, should be a mighty task indeed.

The design of some simple Fresnel lenses shall be conducted to enable evaluation of focusing lenses for use as solar collectors. The focal length of a plano–convex Fresnel lens condenser can be written with the lens formula

$$\frac{1}{f} = \frac{1}{i} + \frac{1}{o} \tag{1}$$

where the conjugates, i.e. the distances of image and object points from the refracting surface of the thin lens, are denoted i, and o, respectively. In case of the plano–convex collector lens, $o = \infty$, and $1/f = 1/i$.

The f/number is a measure for the aperture of the lens. It describes the ratio of effective focal length to diameter of the lens. The f/number is a measure for the flux concentration of the imaging lens; while the geometrical concentration ratio C approaches the theoretical maximum, the heat flux in the focal point is related to the amount of radiation concentrated.

$$f/number = \frac{f}{2R} \tag{2}$$

with R denoting the distance of the extreme paraxial ray from the optical axis of the system. Smaller f/numbers mean larger apertures, and vice versa. Fresnel lenses are free from spherical aberration since every step is designed separately for focusing. Due to their thinness both absorption losses within the material, and the change of those losses over the lens profile are small. Fresnel lenses can be designed as very 'fast' lenses, having a small f/number. Only Fresnel lenses 'faster' than $f/0.5$, i.e. with a diameter twice their focal length are called "impractical" by Fresnel Technologies (1995).

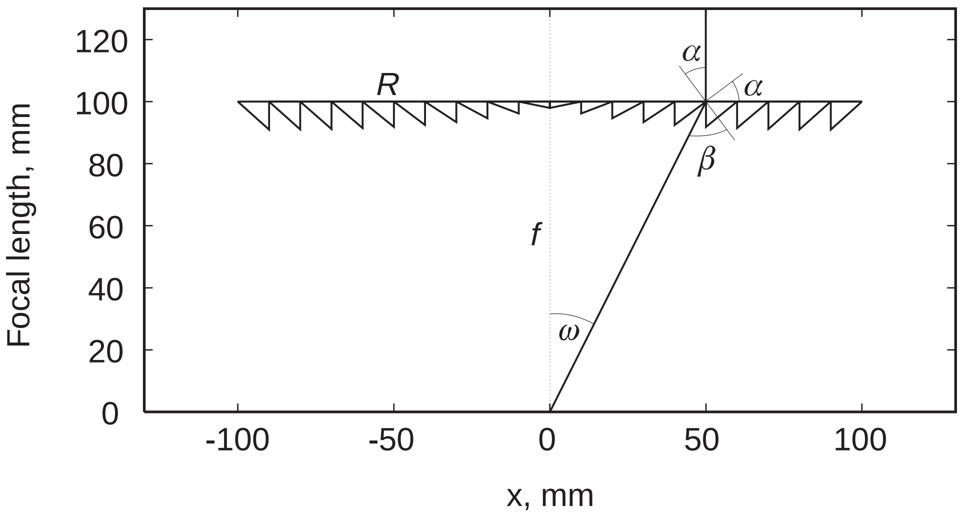

Figure 1: Simple Fresnel lens with grooves facing inward. Analytical solution.

A typical imaging Fresnel lens with grooves facing inwards shall be presented here. The design has an analytical solution, and follows Tver'yanovich (1984). In accordance with Fig. 1, three equations can be set up to describe the lens. The prism angle α is the goal of a simulation written.

$$\begin{aligned} n \sin\alpha &= \sin\beta \\ \tan\omega &= \frac{R}{f} \\ \beta &= \alpha + \omega \end{aligned} \tag{3}$$

Some iterations yield an expression for $\tan\alpha$

$$\tan\alpha = \frac{R}{f}\frac{\cos\omega}{n - \cos\omega} \tag{4}$$

Substutiting $\cos\omega$ with the expression $f/(R^2+f^2)^{1/2}$ gives a final expression for the prism angle α in terms of focal length f, and aperture R.

$$\tan\alpha = \frac{R}{n\sqrt{R^2+f^2}-f} \tag{5}$$

The result of a simulation based on this Eqn. 5 is shown in Fig. 1. From the figure, it becomes obvious that the lens has at its thinnest points no thickness at all. The focal lenght is taken as $f = 100$ mm, and the aperture runs for $0 \leq R \leq R_{max}$, by steps of $R/10$ where $R_{max} = f$ to reach an f/number of 0.5 for this lens. Similar procedures can be applied to generate lenses with grooves facing outward (Tver'yanovich, 1984), or a 'dome' shaped lens, where $f = const$.

4. NONIMAGING FRESNEL LENSES

Shaped Fresnel lenses of bifocal, or nonimaging type are more recently developed lenses for collection of solar rays. Of course, imaging lenses can be designed with curvature, too, but the curvature is most advantagous for solar energy applications with linear nonimaging designs, since light incident from both sides of the optical axis can be concentrated without violating the smooth surface requirement. Most probably, the late W. T. Welford deserves the honour to be credited with the initial idea for the design of curved lenses, based on his experiences with nonimaging optics that led to his and R. Winston's book (Welford, Winston 1978). Collares–Pereira *et al.* acknowledge a private communication with Welford in their first paper on the subject, which in turn is referred to in the first paper of Kritchman's group.

Contrary to imaging devices, nonimaging Fresnel lenses are designed starting not with the focal length of the lens, but with a pair of design angles, termed 'acceptance half angles'. These acceptance half angles are opening the collector's aperture which is explicitly designed to accept rays incident from directions within a certain angle. As opposed to reflective mirrors, the behaviour of lenses depends both on the incidence in the cross–sectional plane, and on the one in the perpendicular plane. When designing collectors with line focus (2D), this makes a difference, as is seen from the prism's optics. Although Collares–Pereira (1979) realizes the importance of the perpendicular fraction of the incoming ray when tracing rays through his lens, he did not include the perpendicular ray into its design. Neither did any of the other authors listed before 1999, even though most lenses for solar energy applications are expected be used as linear 2D–concentrators, with N–S orientation and daily tracking.

An example for a nonimaging linear lens for daily tracking and seasonal tilt is given in Fig. 2. The lens 'sees' a fraction of the sky defined by its acceptance half angles θ and ψ. Light incident within these angles is refracted upon the absorber. The system being nonimaging, there is a rather diluted linear image of the sun on the absorber, reducing the 'hot spot' problem of imaging concentrators.

Collectors with rotational symmetry (3D) offer the possibility of higher concentration, and flux ratios, but are usable only with accurate two–axis tracking. Line focusing lenses are suitable for one–axis tracking, as the perpendicular design angle is causing less severe focal forshortening than the cross–sectional acceptance half angle. Linear nonimaging Fresnel lenses can be used as stationary concentrator with small concentration ratios, thus overcoming the focal shortcomings of imaging devices.

5. CONCLUSIONS AND COST CONSIDERATIONS

This paper lists some design principles used and assumptions made by the designers of various Fresnel lenses that have been developed in the last 250 years. Interest in Fresnel lenses for solar energy applications rose in the latter half of the 20th century due to the availability of plastics, especially Polymethylmetacrylate (PMMA) which has a good transmissivity and resistance for sunlight. The design of more and more sophisticated Fresnel lenses goes along the lines of two related developments. Man-

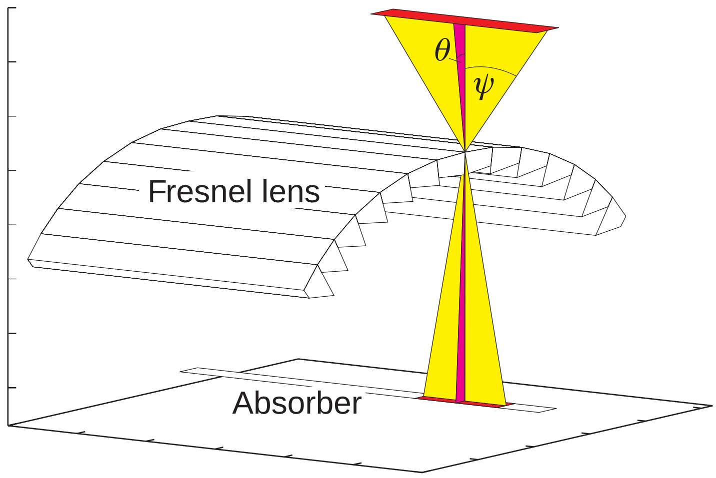

Figure 2: Nonimaging linear Fresnel lens numerically designed by Leutz *et al.*, 1999. Schematic of acceptance half angles: cross–sectional θ and perpendicular ψ. Oversized prisms.

ufacturing technology has improved from moulding, grinding, and polishing glass by hand to diamond turning machines operating at accuracies of less than 1/1000 mm. For many design problems in optics there are no analytical solutions. Only with the help of numerical simulations by computer, available since the 1970's, modern Fresnel lenses can be calculated.

Two design trends can be observed:

- Imaging, often flat lenses focusing paraxial rays with concentration ratios ideally approaching infinity; these systems need accurate two–axis tracking. Their suitability for most solar applications is questionable due to their sensitivity of tracking, or manufacturing errors. Even the size of the solar disk could pose a problem. Judged from our own experiments with shaped imaging lenses, it can be said that focal aberrations with imaging Fresnel lenses are impractically large for their use as solar concentrators, unless high precision tracking is to be employed. Even if the absorber should be designed larger, and positioned closer to the back of the lens, the moving focus would soon exceed the scope of the receiver. Additionally, imaging lenses create a more or less defined focal area, which leads to 'hot spots' on oversized absorbers. Thus, the only way to successfully utilize imaging Fresnel lenses in solar energy concentration is to employ accurate tracking.

- Nonimaging, most often convex shaped lenses for low and medium concentration, one–axis tracking, or stationary collectors. Nonimaging Fresnel lens concentrators are thought to be very competitive solar collectors. Their optical qualities approach those of the CPC collector family (Lorenzo, Luque 1982). Fresnel lenses are lightweight, and cost effective. If tracking requirements are kept to a minimum, savings in crystalline photovoltaic surface area due to concentration will off set the cost of the Fresnel lens. O'Neill (1994) expects a levelized electricity price for large photovoltaic systems incorporating Fresnel lenses, and produced at a rate of 30 MW/a, of US 7-15 cents/kWh.

Of the more sophisticated lenses mentioned, some have never left the computer of the designer, some prototypes have been built, and only the imaging lens of O'Neill (1978, 1992, 1994) has found its way to mass–production. A company has been set up in 1983, found support with the United States Department of Energy, and supplies photovoltaic modules incorporating the lens. The largest projects using the two–axis tracking systems are two plants of 100 kW each, in Texas, U.S.A. Although convex shaped, nonimaging lenses can be manufactured as flat lenses and bent into shape, significantly lowering manufacturing complexity. As the solar market grows, Fresnel lenses, in particular nonimaging devices, are expected to increase their share.

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