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Durability of Fresnel lenses: A review specific to the concentrating photovoltaic application

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ABSTRACT

The durability of Fresnel lenses used in the concentrating photovoltaic (CPV) application is reviewed from the literature. The examination here primarily concerns monolithic lenses constructed of poly(methyl methacrylate) (PMMA), with supplemental examination of silicone-on-glass (SOG) composite lenses. For PMMA, the review includes the topics of: optical durability (loss of transmittance with age); discoloration (the wavelength-specific loss of transmittance); microcrazing and hazing; fracture and mechanical fatigue; physical aging, creep, shape change, buckling, and warping; and solid erosion. Soiling, or the accumulation of particulate matter, is examined in the following contexts: its magnitude of reduction in transmittance; variation with time, module tilt, and wavelength; the processes of adhesion and accumulation; particle size, distribution, composition, and morphology; and its prevention. Photodegradation and thermal decomposition, mechanisms enabling aging, are examined relative to the CPV-specific environment. Aspects specific to SOG lenses include: solarization of the glass superstrate; corrosion of glass; delamination of the silicone/glass interface; change in focus due to thermal misfit between the laminate layers; and the chemical stability of poly(dimethylsiloxane) (PDMS). Recommendations for future research are provided, based on the most important and the least explored topics.

1. Introduction

Concentrating photovoltaic (CPV) technology uses relatively sizable optical component(s) to focus optical flux onto a relatively small photovoltaic (PV) cell [1]. The CPV application becomes economically advantageous when the module cost is reduced using optical components that are inexpensive relative to the PV cell. To realize low levelized cost of electricity, the optical components must provide good performance over the desired service life of 30 years. Although the advancement of high-efficiency PV cells (such as multijunction III–V technology) has recently motivated interest in CPV, understanding related to the durability of the optical components remains limited.

Refractive CPV technology typically uses a lens as the first component of an optical system. Fresnel lenses consist of discrete concentric prism elements patterned on a superstrate. Fig. 1 represents a typical Fresnel lens, which may be constructed monolithically or out of separate layers of material. Since their first application as a collimator in a lighthouse in 1822 [2], Fresnel lenses have been used where the size, weight, and cost of a spherical lens element would be prohibitive. As CPV modules are typically mounted on a tracker made to point toward the sun, Fresnel lenses have traditionally been manufactured out of poly(methyl methacrylate) (PMMA). Such lenses may be manufactured by hot-embossing, casting, extruding, laminating, compression-molding, or injection-molding thermoplastic PMMA [4]. A heavier, but less researched, lens technology consists of acrylic or silicone facets patterned on a glass superstrate [3,5].

Certain optical considerations are relevant to the discussion of Fresnel lenses. For example, the prism side of the lens is typically mounted facing the inside of a CPV module (as indicated in Fig. 1), because the prism valleys are less likely to become contaminated ("soiled") with particulate matter, the smooth superstrate surface may be more readily cleaned, and the transmission loss through the lens is reduced [6,7]. Fresnel lenses may be designed to focus flux at a spot or along a line. The concentration of flux that may be realized in these geometries is represented in Eq. (1) [2,8], where for system international (SI) units, C_{max} represents the maximum concentration of optical flux (unitless); n is the real component of the refractive index (unitless); and θ_a and ψ_a are the acceptance angles (also known as the "half field of view" (HFOV)) of the incident flux relative to the lens (radians):

$$C_{max} = \frac{n^2}{\sin[\theta_a]\sin[\psi_a]} \Rightarrow \frac{n}{\sin[\theta_a]} \quad (1)$$

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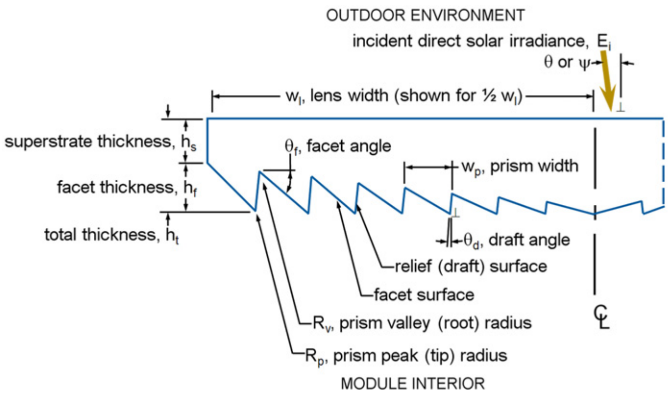

Fig. 1. Cross-section schematic that identifies the key features of a typical Fresnel lens. The orientation relative to the sun and interior of the module is labeled. Adapted from [3].

From Eq. (1), the C_{max} that may be realized for imaging PMMA optics (a solid lens in air, where $n\sim1.003$) is roughly 46,300× for spot focus and 215× for line focus, for the angular radius of the sun, i.e., 4.653 mrad [2]. In practice, a geometric concentration (C_g) much less than the thermodynamic limit [9], e.g., C_g=5×–1000×, is used to allow an optical tolerance, e.g., accommodation of tracking error. Regarding lesser optical concentration, studies have suggested that linear concentrators with C_g=2.1× [6] or 15.6× [10] can harness the direct and circumsolar region (the angular radius of ~50 mrad) without tracking the sun [8]. The exact concentration limit for non-tracking CPV is debated, e.g., the maximum C_g of 2.3× in air is identified to be improved to C_g=5.2× using a solid glass or polymeric optic [11].

Mechanical stiffness and the corresponding tracking-error tolerance (as well as the flux concentration) can be improved, whereas chromatic aberration and module thickness (lens-to-cell separation distance) are reduced if a domed (rather than flat) Fresnel lens geometry is used [2,6,7,12]. From analysis, the lens comes to increasingly resemble an ideal Lambertian source if a flat, roof, arch, or domed-shape lens is used [6,12].

The issue of chromatic aberration is important to CPV because heterogeneous color distribution adversely affects the PV efficiency [13,14]. In "ordinary dispersion," the n of the lens material decreases with λ [15], making blue light focus further from the lens than red light. The photovoltaic efficiency is then reduced because the size of the image is increased (for all cells) and because the spectrum varies with location on the cell (for multi-junction cells). This heterogeneous color distribution on a multi-junction cell causes a detrimental (current-limiting) spatial variation in the photocurrent generation for each junction (unless it can be redistributed laterally within the cell [16]).

Light loss (optical efficiency), chromatic aberration, tracking-error tolerance, spot shape, and flux uniformity may be improved using a non-imaging lens design, which must be analyzed using ray-tracing software [2,10,18]. The same factors can also be addressed using a secondary optic. A sharp-cornered square, triangular, hexagonal, or rectangular light-pipe composed of glass [17,19–22] or metal [23] can be used to homogenize optical flux. A light pipe using a rounded cross-sectional geometry would instead render the opposite flux distribution, i.e., with concentration increase from the edge to approach infinity at the center [19,20]. Glass "kaleidoscope homogenizers" operate on the principle of total internal reflection, which may render a minimum-to-maximum irradiance ratio of 0.94 when the focused flux is reflected twice (on average) within the optic [21]. In contrast, the flux distribution may easily vary by one to three orders of magnitude if no secondary optic is used [24,25]. The chromatic and flux uniformity rendered by a secondary optic usually improves the PV efficiency beyond the expense of the optical loss associated with the secondary. Other examples of secondary optics include lenses of a spheroidal [25] or sphere-plus-cone [25] geometry, or reflectors including linear, elliptical, or hyperbolic mirrors [6] situated about a linear concentrator.

The f-number, N (unitless), is a related concept. For imaging optics, N relates the focal distance, f (m), to the beam radius, R_b (m), i.e., $N=f/(2R_b)$. In CPV, N specifies the compromise between the thickness of the module (which decreases as N is decreased) and the issues of chromatic aberration, tracking-error tolerance, alignment tolerance, spot shape, and flux uniformity, which become increased as N is decreased.

Ranges of values specific to Fresnel lenses used in CPV are provided in Table 1. The values in Table 1 come from the historic literature (originating in the 1970s), as well as literature describing contemporary products. The table is neither meant to guide CPV module design, nor does it imply the most advanced manufacturing capability; rather, the values are meant to provide a figure of merit for reference, aiding discussion as durability issues are examined. In Table 1, η_e refers to the overall optical efficiency of the lens, including: reflections at the free surfaces, losses at the tip radii, draft angle losses, and optical absorptance (at wavelengths outside of specific absorption regions).

Key characteristics of materials including PMMA, poly(dimethylsiloxane) (PDMS, moderately and highly cross-linked), soda-lime glass, and aluminum (often used in CPV modules) are provided in Table 2. The values in the table apply to unaged material. Like Table 1, Table 2 provides representative values to aid discussion. The values in the table (except for θ_c) were obtained from manufacturer's data [26] and were not independently verified at the National Renewable Energy Laboratory (NREL). The maximum strain, ε_m, is given when the mode I critical fracture toughness, K_{IC}, was not available. Applicable formulations of optical- or mirror-grade PMMA material may come from the automotive, lighting, or skylight industries. Applicable formulations of optical-grade PDMS material are shared with the aerospace, electronic, and light-emitting diode industries (but typically excluding the health, industrial, and automotive industries). PMMA and PDMS may be adhered to a glass superstrate and patterned as a Fresnel lens. Applicable formulations of PDMS are typically cured from a two-part system and are colloquially known as "gels," "elastomers," or "encapsulants." Polycarbonate (PC) is a material sometimes suggested as an alternative to PMMA. The significantly greater toughness prevents mechanical fracture and fatigue in PC, but PC is less scratch resistant than PMMA [27]. Although not explored here, potential disadvantages of PC include its lesser spectral bandwidth [15], lesser optical transmittance [15], greater optical dispersion (enhancing

Table 1
For Fig. 1, representative geometry and parameter values for a CPV Fresnel lens.

Parameter name	Symbol	Representative value
Facet thickness	h_f	0.1–0.5 mm
Superstrate thickness	h_s	2.0–5.4 mm
Total lens thickness	h_t	2.5–5.5 mm
Prism peak radius	R_p	2–30 μm
Prism valley radius	R_v	1–30 μm
Facet angle	θ_f	0–1.6 rad
Draft angle	θ_d	35–52 mrad
Prism width	w_p	0.01–1.0 mm
Lens width	w_l	2–30 cm
Acceptance angle (HFOV)	θ_a	0–300 mrad
Geometric concentration	C_g	5–1500
f-number	N	0.5–1.5
Optical efficiency	η_e	78–86%