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ScienceDirect
Solar Energy 127 (2016) 285–293
SOLAR ENERGY
www.elsevier.com/locate/solener

Optimize the shape of curved-Fresnel lens to maximize its transmittance

Xinglong Ma [a], Hongfei Zheng [a,*], Meng Tian [b]

[a] School of Mechanical Engineering, Beijing Institute of Technology, Beijing 100081, China
[b] Institute of Sustainable Energy Technology, Department of Architecture and Built Environment, University of Nottingham, Nottingham NG7 2RD, UK

Received 27 July 2015; received in revised form 8 January 2016; accepted 10 January 2016
Available online 15 February 2016

Communicated by: Associate Editor Antoine Bittar

Abstract

This study is to determine the range of incidence angles for a required transmittance of elementary prisms in a curved Fresnel lens and hence to determine the curvature of the lens. The *p-polarized light* and *s-polarized light* is considered separately. Calculations indicated that the transmittance of *s-polarized light* is always lower than *p-polarized light* and the total transmittance generally decreases with the increase of incidence angle monotonously according to the Fresnel equations, and therefore the transmittance of *s-polarized light* was recommended as the target for a lens' design. Stokes' reversible relation was derived by Fresnel formulas, which illustrates the reflectivity on both sides of the interface is equivalent when light goes through two media along with a certain path no matter which direction it is transmitted. It is found there is the optimal transmittance condition of prism (OTCP) when the incidence angle changes for a given refractive index bases on Stokes' reversible relation. According to OTCP, the transmittance of a curved Fresnel lens can be calculated for a given curvature and focus and therefore the shape of lens can be optimized. The incidence angles for the required transmittance values of 0.95, 0.90, 0.85, 0.80 and 0.75, respectively, are given for different refractive indices. For example, for the refractive index $n_{21} = 1.49$ (a value for the common PMMA), the range of incidence angle of *s-polarized light* is 0–22° if the required transmittance is 0.90; it becomes 0–48° when the required transmittance is reduced to 0.80.

Keywords: Curved-Fresnel lens; Solar concentration; Optimal transmittance; Incident angle range

1. Introduction

Solar concentration is the most popular way to collect solar energy to obtain high-temperature thermal energy. Transmission-type Fresnel concentration is much favored by researchers nowadays for its advantages such as low cost, low requirement of tracking, compact volume, lightweight and the convenience of setting up (Xie et al., 2011). Fresnel lenses consist of discrete concentric prism elements patterned on a superstrate (Miller and Kurtz, 2011). In 1951, Miller et al. (1951) designed and fabricated the first plastic Fresnel lens by injection molding. He found the plastic Fresnel lens has high-quality surface and good performance of concentration that are as good as vitreous Fresnel lens. Nelson et al. (1975) designed a line-focus Fresnel lens which was used for heating water. The results show that the focal area's temperature of the Fresnel lens is about 143 °C, while the average optical efficiency is only 50%. Krichman et al. (1979) prompted a new kind of convex-shaped line-focus Fresnel lens, which provided a new idea for shaped-Fresnel lens' studying. It had been proved that its geometrical concentration ratio (GCR) is very close to the theoretical value. In 1980, (Krichman, 1980) took the influences of color and phase differences of solar light into account and designed a convex-shaped Fresnel lens, whose GCR reaches to 80. Nakata et al. (1980) designed an imaging point-focus spherical Fresnel

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* Corresponding author. Tel.: +86 010 68915210.
E-mail address: hongfeizh@bit.edu.cn (H. Zheng).

http://dx.doi.org/10.1016/j.solener.2016.01.014
0038-092X/

Nomenclature

i_1	incident angle
i_2	refractive angle
n_{21}	relative index of refraction
$\tilde{E}'_{1p}$	complex amplitude of *p-polarized light* of reflected light
$\tilde{E}_{2p}$	complex amplitude of *p-polarized light* of transmitted light
$\tilde{E}'_{1s}$	complex amplitude of *s-polarized light* of reflected light
$\tilde{E}_{2s}$	complex amplitudes of *s-polarized light* of transmitted light
$\tilde{r}_p$	reflectivity of the complex amplitude of *p-polarized light*
$\tilde{r}_s$	reflectivity of the complex amplitude of *s-polarized light*
$\tilde{t}_p$	transmittance of the complex amplitude of *p-polarized light*
$\tilde{t}_s$	transmittance of the complex amplitude of *s-polarized light*
R	reflectivity
T	transmittance
R_p	reflectivity of *p-polarized light*
R_s	reflectivity *s-polarized light*
T_p	transmittance of *p-polarized light*
T_s	transmittance of *s-polarized light*
I	light intensity
I_p	light intensity of *p-polarized light*
I_s	light intensity of *s-polarized light*
OTCP	the optimal transmittance condition of prism

lens. The lens performs well on concentrating homogeneity. The transmittance of it reaches to 83%. It was applied for low power photovoltaic power generation and tracked by polar axis. Mijatovic et al. (1987) designed a solar concentrating system with cylindrical Fresnel lens. The experiment results show the photoelectric conversion efficiency is higher than 30% after considering the homogeneity of energy distribution. So it can be successfully applied to high power photovoltaic power generation. Soluyanov and Grilikhes (1993) put forward a theoretical calculation method which can be used for analyzing the factors that affect the distribution of energy intensity, including designing and calculating error and manufactural difference. Khalil et al., (1998) designed a flat plate line-focus Fresnel lens. The experimental results illustrate that the middle part of the lens has high optical efficiency. However, optical efficiency drops rapidly when it gets close to the edge of Fresnel lens because of the sharp increase of reflection loss. So the average optical efficiency is barely 58%. Leutz et al. (1999) designed and manufactured a non-imaging dome-shaped line-focus Fresnel lens based on the edge lights principle. This lens has several advantages such as short focal length, wide receiving angle and high GCR. The average optical efficiency of the lens is 72%. In 21st century, the application of Fresnel lens becomes wider and wider. Adeff and Hofler (2000) built a thermoacoustically driven thermoacoustic refrigerator power by solar thermal energy. A 0.457 m diameter Fresnel lens focused sunlight onto the hot end of a 0.0254 m diameter reticulated vitreous carbon prime mover stack, heating it to 475 °C in order to eliminate the need for the most troublesome component in heat driven prime mover, the hot heat exchanger. The high intensity sound waves produced by the prime mover could drive the refrigerator to produce 2.5 W of cooling power at a cold temperature of 5 °C and a temperature span of 18 °C. Tsangrassoulis et al. (2005) combined Fresnel lens with core liquid fiber to achieve transmitting daylighting. They tested the efficiency of this heliostat-liquid fiber optic lighting system and estimated the possible energy saving of a windowless room, and obtained positive results. Yabe et al. (2007) employed 1.3 m^2 area size Fresnel lens to achieve the solar-energy-pumped laser. All the system was in one unit and moves together. Once the alignments of laser cavity were fixed, realignment would not be necessary even if all the system moved following the sun. The energy conversion efficiency of it is 11–14%. (Yeh, 2009) formulated an elliptical-based Fresnel lens concentrator system to illustrate the solar spectrum distributions under a Fresnel lens. It can be used to investigate each spectral segment's distribution patterns and help to match the concentration patterns of different wavelengths to different solar energy applications. Li et al. (2013) developed a fundamental modeling for the optical features and control algorithm for a solar stove heat collection system which uses a giant Fresnel lens. The results were incorporated into the control algorithm which has been implemented in the control system of a prototype solar stove which successfully demonstrated the predicted efficient solar tracking. In view of the energy loss over the process from light concentration to utilization of thermal energy, Shatz et al. (2010) put forward a concept of thermodynamic efficiency which can measure the performance of a concentrating system comprehensively. Hornung et al. (2012) investigated the influence of temperature of Fresnel lens on energy generation for photovoltaic system. One Fresnel lens was kept at a constant temperature and another with a realistic temperature. Compared to the simulation, poly Fresnel lenses and SOG Fresnel lenses show comparable energy harvesting efficiency and are close to market requirements. Zheng et al. (2014) considered the factors, such as manufacturing error, tracking error and the working surroundings, which influence the concentrating performance of Fresnel lens significantly and then designed and manufactured a cylindrical compound Fresnel solar