The Distance Temperature Map as Method to Analyze the Optical Properties of Fresnel Lenses and their Interaction with Multi-Junction Solar Cells

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Abstract. The optical efficiency of Fresnel lens based solar concentrators varies with the temperature of the Fresnel lens. The dependency of any quantity of interest (e.g. optical efficiency) on Fresnel lens temperature can be visualized by 2d color plots that simultaneously show it as a function of the distance between solar cell and Fresnel lens and as a function of Fresnel lens temperature. This visualization, which is called DTmap, strongly facilitates the analysis of the thermal behavior of a Fresnel lens and the optimization of module height. Based on DTmaps we reveal and discuss serveral details of the thermal behavior of silicone on glass (SOG) Fresnel lenses. In addition, the DTmap is shown for the efficiency of a system consisting of a Fresnel lens and a lattice matched three-junction and a four-junction solar cell. The results demonstrate that the interaction of the concentrator optics and the solar cell is not trivial and may also be studied using DTmaps.

INTRODUCTION

Silicone on glass (SOG) Fresnel lenses have gained a significant market share of all high concentrating photovoltaic (CPV) systems. It is known from several theoretical and experimental works that the optical performance of this type of Fresnel lenses varies with the lens temperature [1-5]. The physical effects underlying this temperature dependence are a temperature dependent refractive index and a deformation of the Fresnel lens structure due to the difference in the coefficients of thermal expansion of glass and silicone [1]. This temperature dependence influences the energy generation in concentrator photovoltaic (CPV) systems [6].

We introduce a representation called distance temperature map (DTmap) that visualizes the consequences of thermal influences on the optics in a way that intuitively reveals details of the thermal behavior of a SOG Fresnel lens and its interaction with a multi-junction solar cell. Furthermore, we use the DTmap to analyze the thermal behavior in detail. Although this analysis is done using a specific example system, many findings that are presented in the following apply to SOG concentrator Fresnel lenses in general. Finally, we demonstrate the strong interaction between the concentrator optics and the multi-junction solar cell by showing two DTmaps of systems using the same Fresnel lens concentrator but two different solar cells.

THE DISTANCE TEMPERATURE MAP

A DTmap is a 2D color plot that shows a quantity of interest intuitively not only as a function of the Fresnel lens temperature, but additionally as a function of the distance between Fresnel lens and solar cell (module height), motivated by the dependence of the refractive index on temperature. The refractive index of most materials decreases with increasing temperature resulting in an increase of focal length with increasing temperature. In consequence the module height of a CPV module that is required for maximum power output varies with the temperature of its concentrator Fresnel lenses, which is visualized by a DTmap in an intuitive way. Example DTmaps are shown in Fig. 1 and Fig. 2. The quantity plotted on the color scale may be monochromatic optical efficiency as in Fig. 1, the efficiency of electrical power generation as in Fig. 2, or any other quantity of interest.

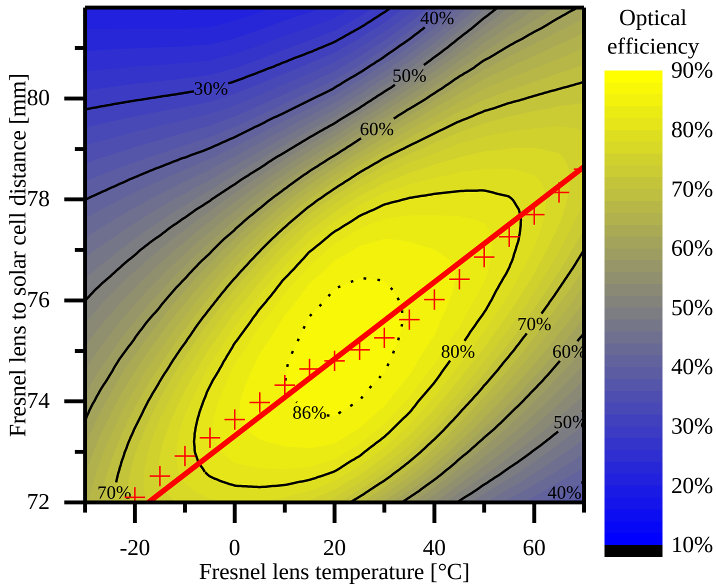

FIGURE 1. DTmap showing the monochromatic optical efficiency at 622 nm wavelength for a specific SOG Fresnel lens. A red line is added to the plot showing the change of focal length solely caused by the temperature dependence of the refractive index. The red crosses mark the focal length (maximum optical efficiency) including the deformation of the Fresnel lens structure.

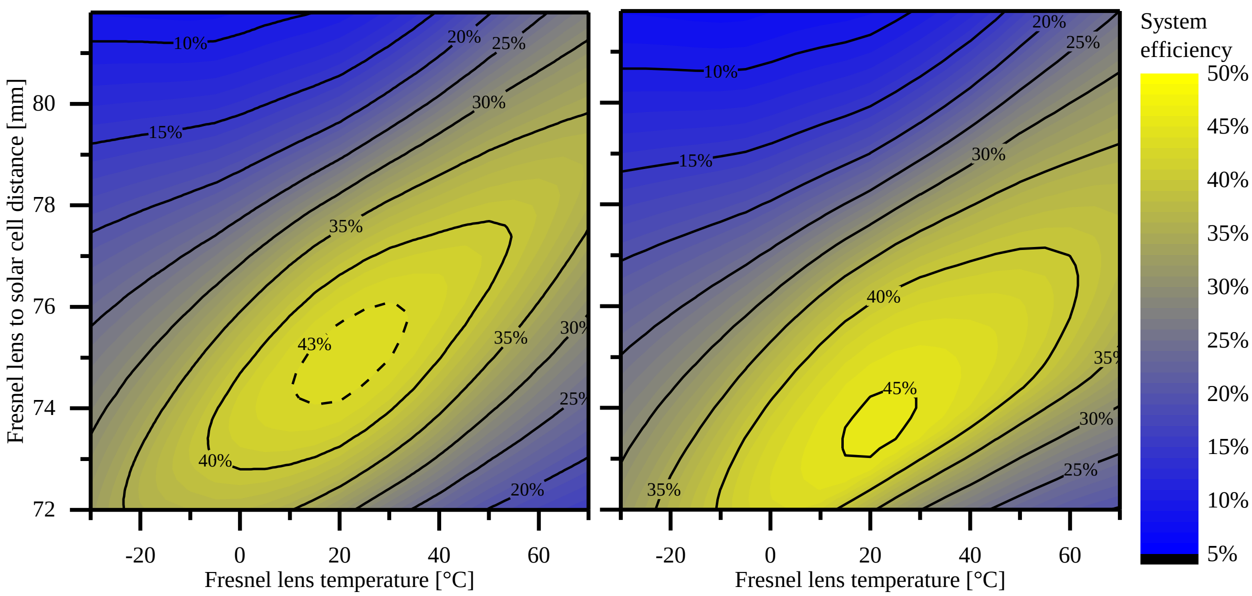

FIGURE 2. DTmaps showing the simulated energy conversion efficiencies of two 509x concentrating systems, both consisting of a specific SOG Fresnel lens and an idealized multi-junction solar cell performing at the Shockley-Queisser-limit. The two systems only differ in the solar cell. Left DTmap: lattice matched triple-junction solar cell (1.87 / 1.41 / 0.66 eV), right DTmap: four-junction solar cell (2.13 / 1.55 / 1.13 / 0.71 eV).

DETAILED ANALYSIS OF THE TEMPERATURE DEPENDENCE OF A SILICONE ON GLASS FRESNEL LENS

Figure 1 shows a DTmap for monochromatic optical efficiency of an example SOG Fresnel lens. The DTmap was generated via computer simulations using an optical wavelength of 622 nm. The angular distribution of the irradiance follows the "DLR mean" sunshape given in [7] which was additionally convoluted with a Gauss function with σ = 0.1° standard deviation to account for tracking and alignment errors of the CPV system. This and the optical concentrator system matches the system used in [6]. It consists of a 40 x 40 mm² Fresnel lens focusing the light on a circular 2 mm diameter target area. The geometric concentration is 509x. For the purpose of this paper, the curing temperature of the SOG lens was assumed to be 20°C. Visualizing the simulation results as DTmap in Fig. 1 facilitates the detailed analysis of the influence of lens temperature on the optical properties of the Fresnel lens. The accuracy of our simulations has been validated by experiments, as published earlier [3].

Figure 1 contains a red line showing the change of focal distance with temperature that is calculated solely from the change of the refractive index. The red crosses mark the distances between Fresnel lens and solar cell that actually maximize the optical efficiency for each simulated temperature taking into account not only the change of refractive index but also deformations of the Fresnel lens structure due to the different coefficients of thermal expansion of glass and silicone. If the lens structure deformation broadened the focal spot but did not influence the focal length, the optical efficiency of the Fresnel lens would change along the red line in Fig. 1. In that case this line would still go through the maximum optical efficiency value for each temperature. Instead, a comparison of the positions of the red crosses relative to the red line reveals a small region close the curing temperature of the Fresnel lens (20°C) where the deformation of the Fresnel lens structure reduces the shift of the focal distance due to the temperature dependence of the refractive index. The change of focal length and the deformation of the Fresnel lens structure are thus not completely independent of each other, but their interaction remains very small. In consequence the assumption that both effects are independent is a valid approximation for most cases of practical relevance.

Usually, it is assumed that the Fresnel lens recovers its designed shape precisely at the temperature that matches the temperature during the curing of the silicone. Often it is assumed that the Fresnel lens reaches its overall maximum efficiency at this temperature [2, 5]. A close inspection of the distance-temperature-map in Fig. 1 reveals that the optical efficiency maximum is 1 K to 2 K above the simulated curing temperature of 20°C. The reason for the shift involves the draft facets of the Fresnel lens prisms. With increasing temperature these facets become steeper (see Fig. 3). This reduces the shading of incident light by the draft facets and thereby increases the optical efficiency of the Fresnel lens, but only as long as the deformation of the refracting facets of the lens remains small enough not to deflect too much light off the target area. While this effect generally applies, the absolute shift depends on specifics like the irradiation conditions, the specific geometry of the optics and the geometrical concentration factor.

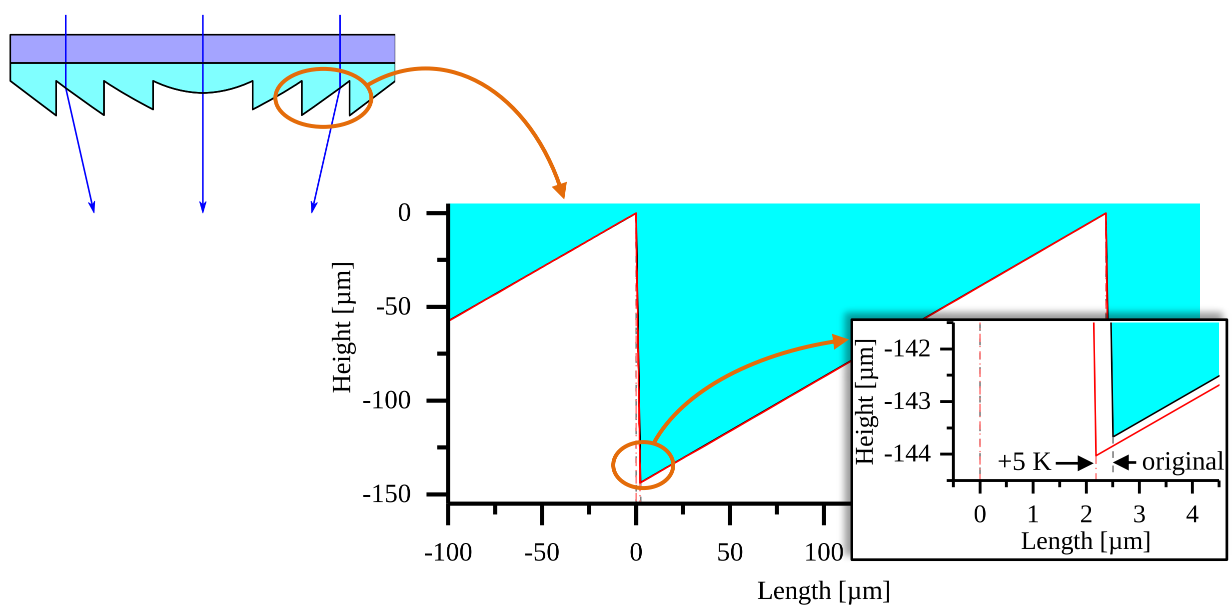

FIGURE 3. Profile of an arbitrary facet of the simulated SOG Fresnel lens. The shaded area above the black line shows the original shape of the facet, the other solid line represents the surface resulting from the finite element method analysis of a 5 K increase in lens temperature. This resulting shape was shifted in the graphic to match the original surface position at the origin of the graph (valley of the structure). The deformation of this Fresnel facet reduces the projected draft area by approximately 13% for this facet (position of edges indicated in the inset).

INTERACTION OF OPTICS AND SOLAR CELL

Plotting the efficiency of electrical power generation facilitates the optimization of a CPV module to a specific distribution of Fresnel lens temperatures. The left DTmap of Fig. 2 was generated using the same optical system as described at the beginning of the preceding section but using the ASTM G173 AM1.5d spectrum [8] for irradiation. This example uses an idealized lattice matched three-junction solar cell operating at the Shockley-Queisser-Limit [9] which was simulated with etaOpt [10, 11]. The bandgap energies were set to 1.87 eV, 1.41 eV and 0.66 eV with a top cell transparency of 5.5 % (see [6] and references therein for details). Of course, for an optimization of a real CPV system one would use the measured EQE of a real solar cell or a more sophisticated model of the solar cell [12].

As the distance between the Fresnel lens and the solar cell is fixed in a CPV module, the efficiency of a CPV module varies along a fixed horizontal line in the DTmap during operation. The DTmap can be used to find the Fresnel lens to solar cell distance which maximizes the average system efficiency. This optimum height strongly depends on assumptions on the DNI weighted average lens temperature and in detail even on the correlation of lens temperature, cell temperature and solar spectrum. It therefore may differ for each specific site of installation. An optimization may not only be done globally but also installation site specific if the module height can be adjusted easily during production.

The triple-junction solar cell used in the example shown in Fig. 2, left side, leads to a DTmap showing a system efficiency that is somewhat narrower than the monochromatic optical efficiency in Fig. 1. Apart from that most aspects of the DTmap can be explained by the monochromatic optical efficiency. This is not a general rule. The right DTmap of Fig. 2 shows the same plot as the left DTmap in Fig. 2 but for the four-junction solar cell with band gap energies of 2.13 eV, 1.55 eV, 1.13 eV and 0.71 eV that is given in [13] as being optimized for maximum power output under the ASTM E891-87 spectrum [14] at one sun, but not optimized for equal current generation in the individual junctions. Again, an idealized solar cell as defined by the Shockley-Queisser limit (all junctions connected in series) was simulated with etaOpt [10, 11]. The right DTmap in Fig. 2 is strongly asymmetric and shows the global efficiency maximum at a lens to cell distances that is much shorter than the lens to cell distance for maximum efficiency of the system shown in the left DTmap of Fig. 2.

CONCLUSION

The distance temperature map (DTmap) is a 2D plot of a quantity of interest as a function of the Fresnel lens temperature and the distance between Fresnel lens and solar cell. Computer simulation results or measurement results may be visualized as DTmap to analyze the influence of Fresnel lens temperature and to optimize the CPV module height. Furthermore the DTmap can be used to analyze the interaction between the concentrator optics and the solar cell. This was demonstrated using the example of an idealized three junction and an idealized four junction solar cell.

Using the DTmap we analyzed details of the thermal influence on the optical performance of a silicone on glass (SOG) Fresnel lense as an example. It was shown that there are small but visible interactions between the change in refractive index and the thermomechanical deformation of the lens structure. There is a small temperature region close to the temperature of Fresnel lens production where the thermal deformation of the Fresnel lens prisms slightly reduces the shift in focal length caused by the change of refractive index of the lens silicone. Furthermore, the maximum optical efficiency of a Fresnel lens is not reached at lens curing temperature, but at a slightly higher temperature due to reduced losses at the draft facets of the Fresnel structure. Even though these effects will apply for most SOG Fresnel lenses, the detailed results will vary for different SOG Fresnel lens, optical system, solar cells, module and application/site specifics.

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