Comparative Study of Fresnel Lenses and Mirrors in Concentrated Solar Applications

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ABSTRACT

This paper evaluates the optical behavior of linear Polymethylmethacrylate Fresnel lenses in Concentrated Solar Power (thermal applications), and compares it to Parabolic Trough Collector technology. The optical performance of the lens was assessed using the ray-tracing program OptiCAD. Geometrical and surface reflectance losses were calculated to find the transmittance of the lens.

The lens system was compared to a commercial Parabolic Trough Collector; the optical efficiency of the parabolic trough is taken from the manufacturer. Both systems are designed to have a single axis tracker.

The study concludes that both systems have comparable optical performance. The obtained cost figures of Polymethylmethacrylate lenses were higher than the glass mirrors, although, plastic lens material can be cheaper and lenses can be manufactured at lower cost and higher volumes than metal mirrors.

The comparison remains open for many aspects, and the development of such system depends not only on the performance efficiency, but also, strongly, on the economic feasibility, performance track record, and eventually, the bankability state of large scale power plants.

1. INTRODUCTION

The history of solar technology spans from the 7th century B.C. where magnifying glass were used to concentrate sun’s rays to make fire and to burn ants (US Department of Energy, 2001); the developments never stopped ever since. In the second century, the Greek scientist, Archimedes, used the reflective properties of bronze shields to focus sunlight and to set fire to wooden ships from the Roman Empire which were besieging Syracuse. Later in the 1st to 4th centuries A.D. the famous Roman bathhouses had large south facing windows to let in the sun warmth, paving the way for passive design architectural concepts (US Department of Energy, 2001).

With the discovery of the French scientist Edmond Becquerel of the photovoltaic effect in 1839 (US Department of Energy, 2001), another evolution started.

Up until the 1970s, solar technologies were merely a topic of research and prototyping, considering the high costs and unnecessity for such technologies. But when the energy crisis started to unfold in the late 60s and the economies of the major industrial countries of the world were heavily affected and faced petroleum shortages as well as elevated prices. At the same period of time, Dr. Elliot Berman, with help from Exxon Corporation, designs a significantly less costly solar cell, bringing price down from $100 a watt to $20 a watt (US Department of Energy, 2001). Solar cells begin to power navigation warning lights and horns on many offshore gas and oil rigs, lighthouses, railroad crossings and domestic solar applications began to be viewed as sensible applications in remote locations where grid connected utilities could not exist affordably. Several energy research institutions were launched and renewable energy utilization were taken more of a must than a luxury ever since.

In 2012, renewable energy provided an estimated 19% of global final energy consumption (Renewable Energy Policy Network for the 21st Century,2014, 2014); and continues to grow strongly, being aided by continuing advances in technologies, falling prices and innovations in financing, and driven largely by policy support. These developments, escorted with the increasing awareness of renewable energy technologies and resources, and their potential to help meet rapidly rising energy demand,
while also creating jobs, accelerating economic
development, reducing local air pollution and carbon
emissions; makes it more feasible than new fossil and
nuclear installations under many circumstances, and thus,
more affordable for a broader range of consumers in
developed and developing countries.

Concentrated solar energy using refractive and
reflective optical concentrators applies both in
Concentrated PV and Concentrated Solar Power
technologies, presented with the principle of focusing a
large area of sunlight into a smaller area. Yet there isn’t
a clear benefit of using one optical concentrator
technology over the other. This paper is mainly focused
on studying and comparing certain optical properties and
performances of refractive (Fresnel lens based) and
reflective (mirror based) concentrators in solar
applications.

2. METHODOLOGY

A commercialized parabolic trough collector design
was selected for the comparison; and a constant pitch
linear Fresnel lens was designed with the same
dimensions. Both optical models were simulated and ray-
traced using OptiCAD program. Table 1 lists the fixed
parameters and the ones being compared for the lens and
mirror systems in this study.

Table 1: Fixed and compared parameters of the lens
and mirror systems in this study

<table>
<thead>
<tr>
<th>Fixed Parameters</th>
<th>Compared Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometrical concentration ratio.</td>
<td>Focal length.</td>
</tr>
<tr>
<td>Absorber diameter.</td>
<td>Optical Efficiency</td>
</tr>
<tr>
<td>Aperture</td>
<td>Acceptance half angles</td>
</tr>
<tr>
<td></td>
<td>Intercept factor</td>
</tr>
</tbody>
</table>

3. DESIGN OF FRENSNEL LENS

The design of the Fresnel lens in this study was based
on the analytical solution provided by Tver’yanovich in
(Tver’yanovich, 1984). The following equation applies
for calculating the prism angle for lenses with the prisms
facing inwards. Geometry parameters of a flat Fresnel
lens is shown in Error! Reference source not found.

\[
\tan \theta_f = \frac{R}{(n_s \sqrt{(R^2 + f^2) - f})} \quad \text{Equ 1}
\]

(Soud & Hrayshat, 2009)

The prism angle \( \theta_f \) is determined from the specified,
radius R, refractive index n and focal length f. The
prismatic profile of flat lenses may be formulated by
three methods:

1- Constant height: where the thickness of the
supporting layer \( h_s \) (parameters described in
Figure 1) is constant and the facet thickness \( h_f \) is
constant. The disadvantage of this profile is the
variable prism width \( w_p \), which complicates the
production of uniform irradiation on the focal
plane.

2- Constant pitch: where the prism width \( w_p \) is
constant, facet thickness \( h_f \) is variable and the
total thickness \( h_t \) is constant. Considering that
this profile is the most convenient for the
production of plastic Fresnel lenses
(Tver'yanovich, 1984), it was chosen for the
lens design in this study.

3- Constant mass distribution: constant prism
width \( w_p \) and a variable total thickness \( h_t \), the
distribution of mass over the whole area is
uniform.

Figure 1: Cross-section schematic that identifies the
key features of a typical Fresnel
Lens. Source: (Miller D. and Kurtz S., 2011)

4. RAY-TRACING

OptiCAD is a commercially available computer
program for the design and analysis of three-dimensional
optical systems. It utilizes a ray-tracing method that
follows light in the forward direction, starting at the light
source.

The program may be used to simulate a variety of non-
imaging and imaging optical systems and includes
possibilities to model parabolic, elliptical, spherical and
flat mirrors, single- and double-sided reflective surfaces;
apertures of finite extent; multiple sources and detectors;
compound parabolic concentrators; Fresnel lenses;
polygonal faceted objects (that may be translated from a
CAD program); and light sources as well as detectors,
which makes it possible to calculate the irradiance on a
plane. For all surfaces the reflectance and absorptance
may be specified. OptiCAD also includes models for
several types of light scattering that can be applied to the
reflecting surfaces.
5. SIMULATION: THE FRENSLE LENS MODEL

The Fresnel lens model was designed using an excel tool based on the tver’yanovich principle described earlier. The procedure of choosing the optimum focal length for the Fresnel lens included multiple simulations that will be explained in the following sections. Table 2 lists the parameters of the designed Fresnel lens.

Table 2: Parameters of the designed Fresnel lens.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pitch size (mm)</td>
<td>1</td>
</tr>
<tr>
<td>Draft angle (°)</td>
<td>2</td>
</tr>
<tr>
<td>Design refractive index</td>
<td>1.49</td>
</tr>
<tr>
<td>Aperture (mm)</td>
<td>2370</td>
</tr>
<tr>
<td>Focal length (mm)</td>
<td>2800</td>
</tr>
<tr>
<td>Absorber diameter (mm)</td>
<td>42</td>
</tr>
<tr>
<td>Length (m)</td>
<td>6</td>
</tr>
</tbody>
</table>

The Fresnel lens model is shown in Figure 2, the absorber is positioned at the focal plane, the aperture (limiting aperture) is an OptiCAD object which will pass rays that are either outside of its extent (miss the object) or inside of its hole (where the lens is positioned in this case). Other rays will be absorbed. The reason why this object was used is to be able to identify the amount of irradiance incident on the lens surface, and therefore be able to calculate the optical efficiency of the lens.

The absorber diameter was fixed for both systems giving the absorber used in the commercialized parabolic trough chosen for the study. The absorber is also a polygon object; the points of a 21 radius circle were calculated and then translated using a python script into an importable object for OptiCAD. The glass envelope for the tube was not simulated in this model; assuming an absorbance of 1 at the receiver to be able to account for the Fresnel performance at this stage, and scale it depending on the used absorber efficiency in a later stage.

6. SIMULATION: THE PARABOLIC TROUGH MODEL

The design, simulations and analysis of losses was mainly focused on the lens system; the parabolic trough geometry was taken from a readily commercialized product. Table 3 lists the public parameters of the PTC. Some of the PTC geometrical information was not disclosed as being confidential private communication with the manufacturer.

Table 3: Public parameters of the parabolic trough collector.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aperture (mm)</td>
<td>2370</td>
</tr>
<tr>
<td>Focal length &amp; rim angle</td>
<td>Confidential information from manufacturer</td>
</tr>
<tr>
<td>Absorber diameter (mm)</td>
<td>42</td>
</tr>
<tr>
<td>Length (m)</td>
<td>6</td>
</tr>
</tbody>
</table>

Figure 4 shows a drawing of the parabolic trough collector. The optical efficiency of the parabolic trough at normal incident irradiation is taken from the manufacturer to be 0.747. Efficiency curve is shown in Figure 3.

Figure 3: Efficiency curve in the following conditions: DNI = 900 W/m²; Longitudinal incident angle modifier (K_L) =1. Transversal Incident Angle Modifier (K_T) equals 1 for parabolic trough collectors.

The parabolic trough collector is supplied with: selectively coated receiver, weather-resistant low iron tempered glass mirrors and sun tracking drive and motor.
7. SIMULATION: RESULTS AND DISCUSSION

• The lens system was simulated and ray-traced with polychromatic light and the geometrical losses were calculated to find the optical and transmission efficiency of the lens.
• Whereas for time constraints, the PTC simulations did not consider spectral reflectivity or geometrical errors, the optical efficiency of the PTC was readily taken from the manufacturer’s data sheet. This simplification causes a different base for the two compared system’s efficiencies and could be addressed in future work.
• The longitudinal acceptance half angle effect on the lens performance should be simulated together with different transversal half angles in future work.
• To minimize the effect of longitudinal angles, the lens can be tilted to account for the sun angle; this can enhance the optical performance of the system, but on the expense of increased thermal system complexity and cost, by increasing structure requirements, piping and pumping efforts and costs.
• The Fresnel lens is more prone to soiling, considering the groves side of the lens, and would take relatively higher efforts to clean compare to glass mirrors. This could be solved by adding a glass layer under the groves side of the lens, which will add additional reflection and transmission losses.

Table 4 summarises the systems comparison outcomes and parameters.

Table 4: Summary of comparison results.

<table>
<thead>
<tr>
<th></th>
<th>LENS</th>
<th>PARABOLIC TROUGH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>Lens: PMMA</td>
<td>PTC: Highly reflective tempered glass.</td>
</tr>
<tr>
<td>Optical properties</td>
<td>C_{geo} = 56</td>
<td>C_{geo} = 56</td>
</tr>
<tr>
<td></td>
<td>Aperture width = 2370 mm</td>
<td>Aperture width = 2370 mm</td>
</tr>
<tr>
<td></td>
<td>Absorber diameter = 42 mm</td>
<td>Absorber diameter = 42 mm</td>
</tr>
<tr>
<td></td>
<td>Spectral Transmittance = 0.854</td>
<td>publications indicate an average solar weighted direct reflectivity of the silver coated glass mirrors of 93.5%. (Günther M. , Joemann M., Csambor S. , 2011)</td>
</tr>
<tr>
<td>Focal length</td>
<td>2800</td>
<td>Confidential (Private communication with the manufacturer)</td>
</tr>
<tr>
<td>Optical Efficiency</td>
<td>77.3%</td>
<td>74.7%</td>
</tr>
<tr>
<td>Acceptance half angles</td>
<td>$\theta = 0.2^\circ$, $\psi = 9^\circ$</td>
<td>$\theta = 0$, $\psi = 20^\circ$ (estimated from the manufacturer brochure)</td>
</tr>
<tr>
<td>Intercept factor</td>
<td>95 %</td>
<td>Eurotrough registered an intercept factor of 95.5% for an absorber tube with a diameter of 40 mm. (Günther M. , Joemann M., Csambor S. , 2011)</td>
</tr>
</tbody>
</table>

8. CONCLUSION

• The transversal acceptance half angles give an indication of the low tolerance of both systems to tracking errors.
• The lens system requires a longer focal distance than the PTC, which may result in larger sensitivity to tracking errors and focal aberrations, longer path of the concentrated light might also increase the possibility of light scattering before reaching the absorber and a wider spread of light on the focal plane, especially for the light refracted from the outer prisms.

• The longer focal length also means a higher investment costs in the mounting structure of the system.

• The lens system in this study showed a higher optical efficiency than the PTC, but on the expense of a longer focal length.

• Designing a shaped Fresnel lens can increase the acceptance half angles and increase the optical efficiency, also having a constant focal length across the radius of the lens.

• The costs obtained were much cheaper for the parabolic trough, although, plastic lens material can be cheaper, and lenses can be manufactured at lower costs and higher volumes (Leutz R., 1999).

9. REFERENCES