Hamlet Solar Concentrator

El Abaoui Yousri

Institut National des Posts et Télécommunication, rabat Morocco

Pedro Angel Bernaola Galvan

University of Malaga, Spain

Abstract. This work presents the design and numerical modeling of a solar optical concentrator, known as the Hamlet concentrator, using COMSOL Multiphysics. The system combines a Fresnel lens as a primary optical element and a secondary diopter based on total internal reflection (TIR) to enhance the concentration of solar radiation onto a photovoltaic (PV) cell. The optical components were modeled with realistic material properties, including poly(methyl methacrylate) for the TIR diopter and EVASKY S88 glass for protective layers. A digital twin of the concentrator was constructed in a 2D axisymmetric configuration, and ray tracing simulations were carried out using the Geometrical Optics Module. The solar source was modeled with the standard AM1.5 spectrum to replicate real illumination conditions. The study focused on analyzing the concentrator's power distribution, its concentration ability, and the angular dependence of the collected radiation. The results demonstrate the concentrator's potential to significantly increase the optical power delivered to the PV cell, confirming the suitability of the Hamlet design for high-efficiency solar energy harvesting.

I. INTRODUCTION

Nowadays, the effects of climate change represent one of the most pressing challenges that humanity is facing. In this context sustainable energy solutions remain essential for the energetic transition of our society.

Among the various technologies, photovoltaic devices emerged as a pivotal component towards a low carbon future. Photovoltaic cells convert sunlight into electrical energy offering a clean energy source.

Despite their potential, the widespread adoption of photovoltaic systems is blocked by cost and efficiency barriers. Traditional photovoltaic cell size is about 150cm², since they are made of semiconductor materials the overall cost increases by increasing the size of the photocell.

A way to overcome this problem is to use optical elements that redirect the energy received on a larger entrance aperture to a smaller exit aperture thereby increasing the light intensity received by the cell. These kinds of devices are called Concentrators[1]; the figure below shows a basic scheme of such a device.

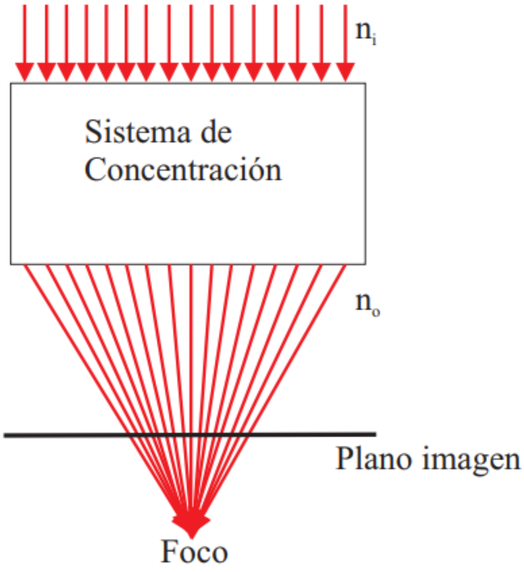

Figure 1.1 : Scheme of a concentrator device

The objective of this Master thesis is to study Hamlet concentrator. The Hamlet concentrator is a two-stage concentrator that possesses an axial symmetry like shown in figure 1.2.

Figure 1.2 : Real Hamlet concentrator

The Hamlet concentrator consists of a Fresnel lens with seven grooves as the primary lens, concentrating light towards the secondary lens which is responsible for distributing the light in the photocell.

The Fresnel lens takes advantage of the laws of reflection and refraction. When a ray travelling through a medium with a refractive index ni crosses another medium with a refractive index nt, part of the energy is reflected, and the other part is refracted through the second medium.

However, if ni > nt light may not enter the second medium and get reflected, this phenomenon is known as total internal reflection (TIR), and occurs for values of the incident angles grater than a certain critical value θ_c known as the critical angle and is given by:

$$\theta_c = \arcsin\left(\frac{n_t}{n_i}\right)$$

This phenomenon is very useful when designing optical devices and especially concentrators[2], in our case it is used in principal diopter also called the diopter (TIR) stands for Total Internal Reflection diopter.

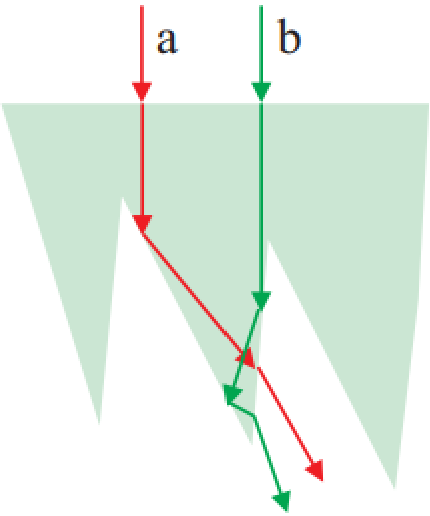

Figure 1.3: Total reflection in a tooth of the TIR diopter

The TIR diopter and the secondary diopter are made with Poly-Methyl-Methacrylat (PPMA).

In this maser thesis we create, using COMSOL software, a digital twin of the Hamlet concentrator constructing the geometry and modelling the materials using the large library of COMSOL materials.

We use the **Geometric optics (gop)[3]** module available in COMSOL to run ray tracing simulations to validate the concentration capabilities of the Hamlet concentrator, we also used the capabilities of the software to model solar illumination using the free AM 1.5 solar intensity distribution data. We also calculated the distribution of power of the concentrated light as a function of the incident angle of the light which is important for designing the optimal geometry of the photocell that will receive light from the concentrator.

II. GEOMETRY MATERIALS AND METHODS

II.1 Geometry construction

The first part of the optical system, which is the TIR diopter part (TIR stands for total internal reflection) is created using sixth order polynomials of the form: $z(r) = \sum_{k=0}^{6} a_k r^k$

Where r(mm) is the radial distance in a cylindrical coordinate system and z(mm) in the height.

The second part constitutes the diopter is constructed using a conical curve of the form $\rho(\theta) = e^{p(\theta)}$where $p(\theta)$ is a polynomial in theta of the form $p(\theta) = \sum_{k=0}^{6} s_k \theta^k$.

In order to create the concentrator in COMSOL we created a 2D geometric part. Then we create as many parametric curves as polynomials. Each parametric curve represents a part of the "theeths" of the concentrator. Note that as the parametric curve in COMSOL is defined in a cartesian (OXY) plan we set the x coordinate to the parameter s and then set the y coordinate to the polynomial z(s). Since the polynomials only forms the "theeths" of the concentrator we close the geometry by adding segments and forming a solid part.

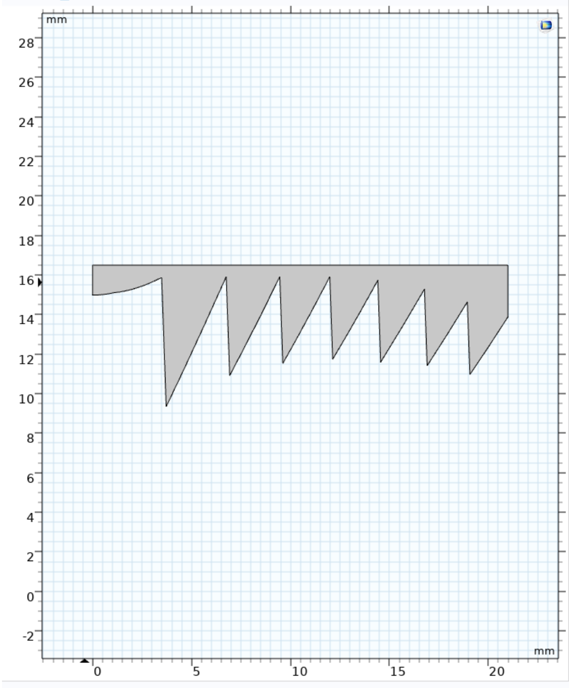

Figure 2.1 TIR concentrator.

The second part consists of the diopter which aims to cover the photocell. In COMSOL it is constructed using an interpolation curve. A python script is used to calculate the interpolated points using the data that provides the coefficients of each polynomial $p(\theta)$. In addition to the diopter an ellipse of diameter of 2mm is added as extra protection to the solar cell. Finally, we get the system geometry.

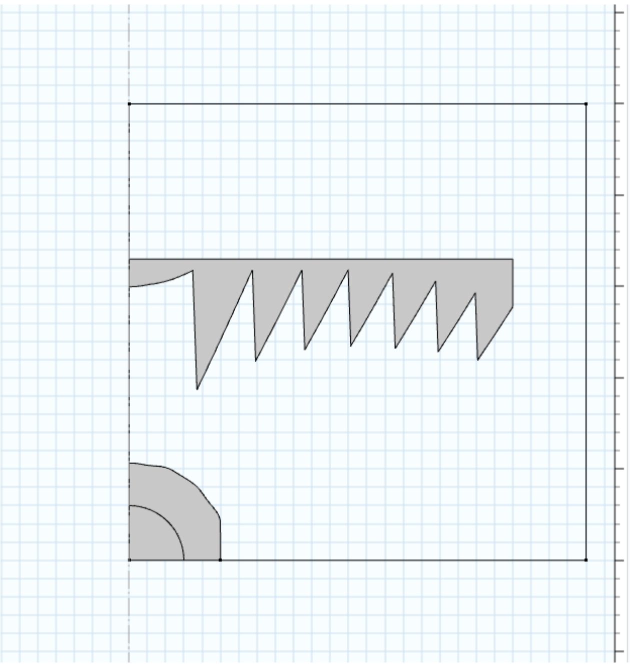

Figure 2.2 Optical system concentrator and diopter

II.2 Materials

There are two materials used in the Hamlet concentrator system. First the Poly(methyl methacrylate) PPMA is used for the TIR diopter part and the secondary diopter. Secondly the EVASKY S88 glass is used for the ellipse part.

II.3 Solar light modelling

The HAMLET concentrator optical system aims to concentrate solar energy, for this we need to model the solar light in COMSOL. To do so we first get the data of the AM1.5 spectral solar energy[4] which represents the spectral irradiance of solar light, function of the wavelength. We then import the data into an interpolation function “int_1” created under the definition node. The function unit is set to 1 (for modeling purpose normally it is W/(m^2*nm)) and the argument unit is set to nm.

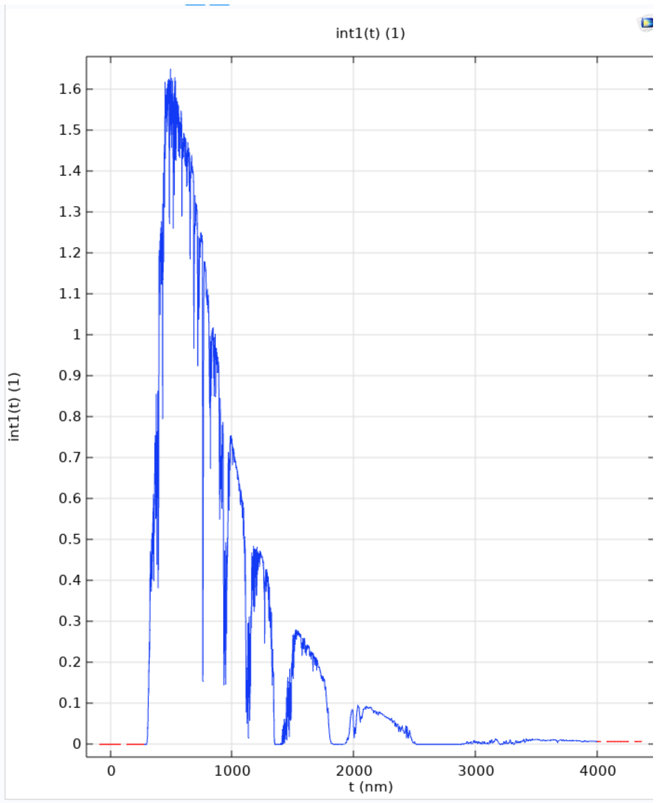

Figure 2.3: Solar power distribution

To generate the solar light in COMSOL we create a “release from grid” node under the geometric optics physical interface. The release from grid node allows us to generate a special distribution of points in space which would correspond to the origine of the light source.

In this release from grid node, we randomly select for each ray a wavelength ranging from 280[nm] to 2500[nm] where lies most of the power of solar radiance. The total source power per unit thickness (Psource) is set to 1000[W/m], and the power is distributed over each wavelength as a function of the solar irradiance created before “int_1”.

II.4 Meshing

For the meshing sequence several rules should be respected in order to get accurate results after the simulation has been done.

First, surfaces that represent a domain (As we are solving a model in a 2D-axis symmetric geometry) can be coarsely meshed) which is the case for the interior domain of the TIR diopter, the secondary diopter and the ellipse.

Secondly, the curved boundaries where the ray interacts with should be finely meshed, it is the case for the boundaries surrounding the TIR diopter, secondary diopter and the ellipse.

Finally, accumulators should also be finely meshed in our case we select a specific size node that we affect to the boundary containing the accumulator and assign to it a custom size of 0.0001m assuming the length of the boundary of the accumulator is 5cm.

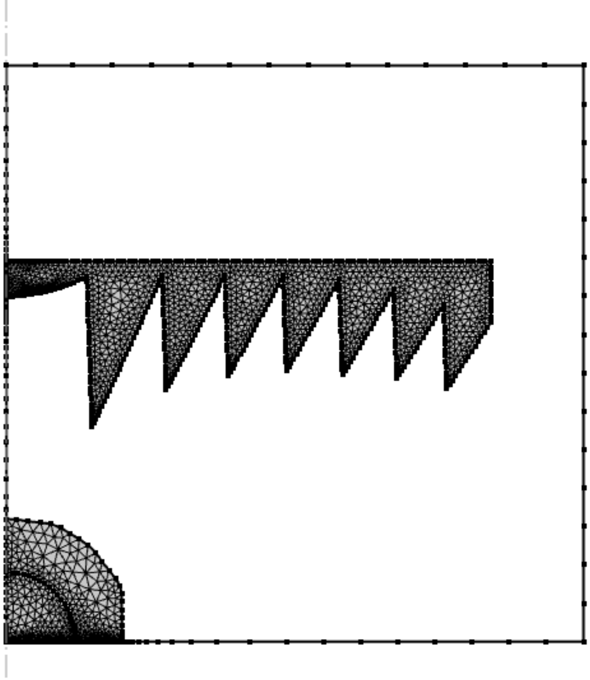

Figure 2.4 : Mesh generation for the Hamlet concentrator

II.5 Model construction

The developed model uses a 2D axis-symmetric geometry. This choice is justified first by the axial symmetry of the hole optical system, and secondly by the fact that we work in the geometrical optics approach which does not involve propagation of modes that could have different 3D shapes like in wave optics.

The refractive index of the exterior domain is set to 1 (similar to air), the refractive index of the interior domains which includes the diopter TIR, the secondary diopter and the ellipse is extracted from material properties, we also select computing the intensity and power of the rays.

The axial symmetry node, which is set by default, replaced by a mirror node to model rays coming out from the TIR diopter and cross away from the limits of the model.

The boundaries of the diopters are modelled using a Material discontinuity node which simulates the Snell's laws for diffraction and refraction.

The photocell is modelled as a boundary which contains the accumulator responsible for computing the power of rays that reach it.

The surrounding boundaries are modelled using wall node in which the rays freeze once they reach the boundary.

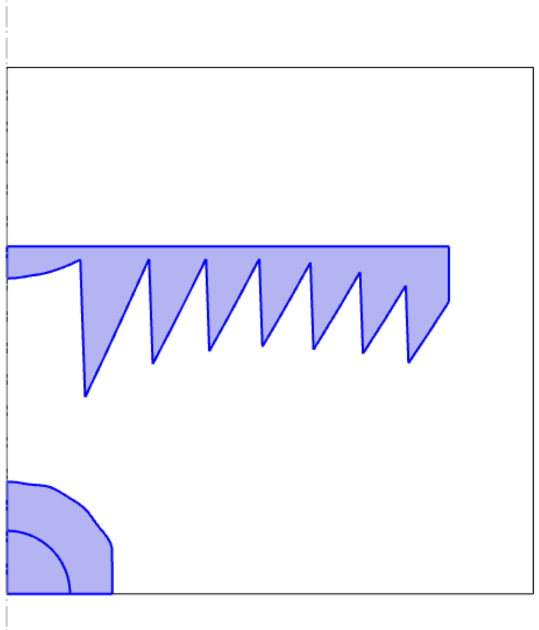

Figure 2.5: COMSOL model of the Hamlet Concentrator

III. THEORY

III.1 Geometric optics

The theory under the geometric optics approach assumes an electric field of the electromagnetic wave in the form:

$$E = ae^{i\varphi}$$

Where a is a slowly varying amplitude and φ is the phase function of the position **q** and the time **t**. The phase of the wave can be expressed as:

$$\varphi = \boldsymbol{k}.\boldsymbol{q} - \omega t + \alpha$$

Where $\boldsymbol{k}$ is the wave vector, $\boldsymbol{q}$ the position, ω the angular frequency, and α is a random phase-shift.

The wave vector and the angular frequency are related in the approximation of geometrical optics by the relation:

$$\omega = \frac{c|\boldsymbol{k}|}{n(\boldsymbol{q})}$$

Where $n(\boldsymbol{q})$ is the refractive index of the medium where the wave propagates. It follows that the wave vector and the angular frequency can be expressed by two following relations:

$$\boldsymbol{k} = \frac{\partial \varphi}{\partial q} \text{ and } \boldsymbol{\omega} = -\frac{\partial \varphi}{\partial t}$$

Following Landau and Liftshitz theory the wave vector and frequency are analogous to the momentum p and Hamiltonian H of a solid particle:

$$\boldsymbol{p} = \frac{\partial s}{\partial q} \text{ and } \boldsymbol{H} = -\frac{\partial s}{\partial t}$$

Here S, is the integral of the Lagrangian along's the particle trajectory.

In its ray tracing algorithm COMSOL computes the ray trajectory and position by solving six coupled first order ordinary equations for the components of **k** and **q**:

$$\frac{\partial \boldsymbol{k}}{\partial t} = -\frac{\partial \omega}{\partial \boldsymbol{q}}$$

and

$$\frac{\partial \boldsymbol{q}}{\partial t} = -\frac{\partial \omega}{\partial \boldsymbol{k}}$$

III.2 Snell's law for medium discontinuity

In order to achieve a concentrator that concentrates light onto a target, the Hamlet concentrator geometry takes advantage of Snell's law for the diffraction and reflection of rays when a discontinuity in the medium is encountered. In COMSOL, the Material discontinuity node serves the purpose of applying Snell's law in discontinuities. When a material discontinuity is encountered the angle of incidence is first calculated:

$$\theta_i = \cos^{-1}\left(\frac{\boldsymbol{n_i}.\boldsymbol{n_s}}{|\boldsymbol{n_i}|.|\boldsymbol{n_s}|}\right)$$

Where $\boldsymbol{n_i}$ is the unit vector of the incident ray and $\boldsymbol{n_s}$ is the unit vector normal to the surface of the discontinuity.

For the refracted ray the direction is given by the following relations:

$$n_t = \alpha n_i + \beta n_s$$

$$\beta = -\alpha \cos(\theta_i) + \cos(\theta_t)$$

$$\alpha = \frac{n_1}{n_2}$$

$$\theta_t = \sin^{-1}(\alpha \sin(\theta_i))$$

With the ray travelling from a medium of index n1 to a medium of index n2.

Also the reflected ray is released at the boundary with the following direction:

$$n_r = n_i - 2n_s \cos(\theta_i)$$

III.3 Fresnel equations

The Fresnel equations describe the reflection and transmission of light when it crosses a medium with a different refractive index.

In our case we are interested in the transmitted and reflected power of light.

For S polarized light the transmittance ts and the reflectance rs are given by the following equations:

$$r_s = \frac{n_1 \cos(\theta_i) - n_2 \cos(\theta_t)}{n_1 \cos(\theta_i) + n_2 \cos(\theta_t)}$$

$$t_s = \frac{2n_1 \cos(\theta_i)}{n_1 \cos(\theta_i) + n_2 \cos(\theta_t)}$$

For a P polarized light, the coefficient of reflection rp and transmission rt are given by:

$$r_p = \frac{n_2 \cos(\theta_i) - n_1 \cos(\theta_t)}{n_1 \cos(\theta_i) + n_2 \cos(\theta_t)}$$

$$t_p = \frac{2n_1 \cos(\theta_i)}{n_1 \cos(\theta_i) + n_2 \cos(\theta_t)}$$

VI. RESULTS SIMULATIONS AND DISCUSSION

VI.1 Concentration Power

The first aspect to study of the Hamlet concentrator is his concentration capability [5]. In order to do so, the first simulation gets rid of the secondary diopter and the ellipse in the geometry of the system, we used a ray tracing study of 1 second and a step of 0.01 second, a solar radiation is used to simulate solar light with a vertical incidence. To plot the received power, we create a revolved 1D surface in the dataset by revolving over the focal segment which carries the accumulator. The plot of power distribution over the revolved surface gives us the distribution of power.

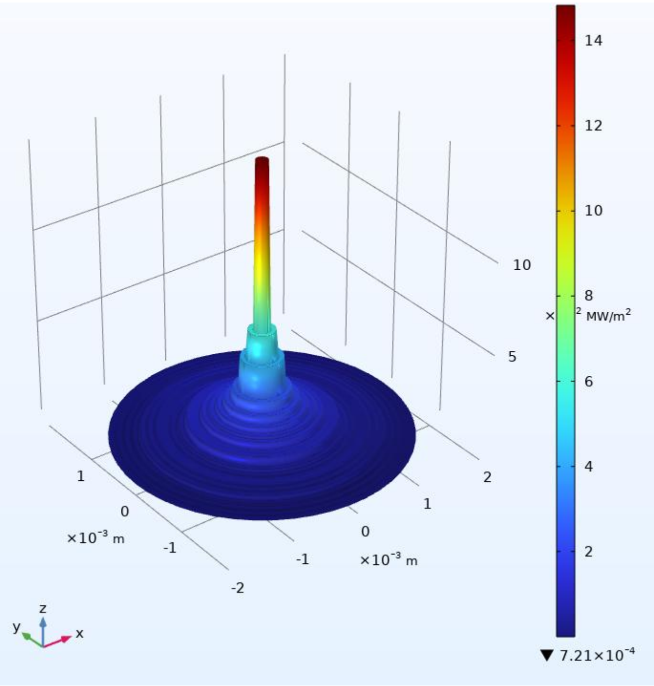

Figure xx 3D power distribution of the TIR diopter

A plot of the accumulated variable density also gives an idea of the concentration ability of the TIR diopter, note that the following plot has a logarithmic scale over the Y-axis.

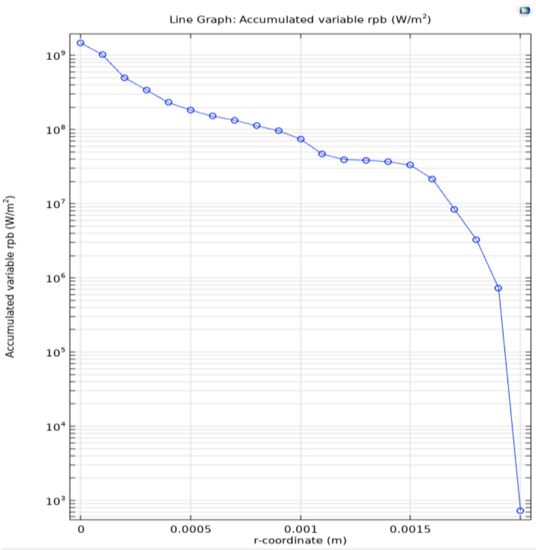

Figure 4.1: Power distribution graph

VI.2 Power distribution function of the incident angle

Another important aspect of a concentrator is to know the geometrical distribution of the output illumination, which is relevant for designing photocells that would have optimal efficiency.

Since there is no direct way to calculate the incident angle of rays in COMSOL, we had to use the ray direction that is computed by the ray tracing algorithm for each ray in order to infer the incident angle.

In order to achieve this, we set the source of the accumulator as a function arctangent of the r component of the direction vector of the ray divided by the z component of the direction vector of the same ray, which gives us the incident angle that range from 0°(parallel to the z axis) to 90°(parallel to the r axis).

The source of the accumulator is then set to:

gop.Q*(atan(abs(kr/kz))<alpha+delta_alpha)*(atan(abs(kr/kz))>alpha)

Which means that the source accumulates the power of rays that have an incident angle between alpha and alpha+delta_alpha, the absolute value is set to include symmetric rays that may have the same incident angle but opposite directions.

To get the distribution of power as a function of the incident angle, we create the two parameters, **alpha** which is the incident angle, set to an arbitrary value of 30° and **delta_alpha** which is fixed to 3°, then we apply a parametric sweep over alpha ranging from 0° to 70° with a step of 5°.

To calculate the total received power as function of the incident angle we perform a surface integral of the power density for each value of alpha by creating a surface integration node and choosing as a dataset Revolution 1D which is the surface created by revolving the segment that has been used as container for the accumulator. The evaluation of this quantity gives us the received power as function of the incident angle. We create then the appropriate graph:

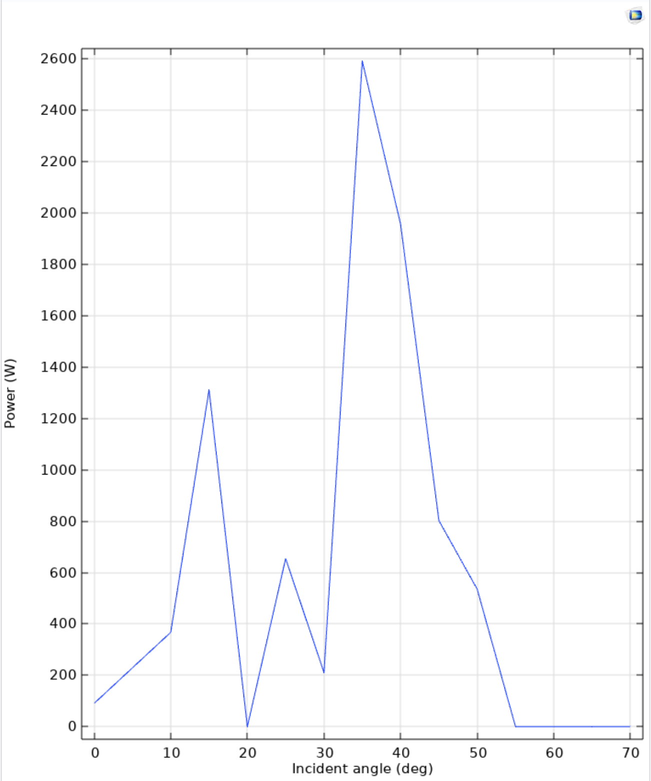

Figure 4.2 : Power distribution as a function of the incident angle

V. CONCLUSIONS

The numerical study of the Hamlet concentrator has shown that the combination of a Fresnel lens and a TIR-based secondary diopter provides an efficient optical configuration for concentrating solar radiation. The simulations highlight the device's ability to increase the local irradiance on the photovoltaic cell while maintaining a compact geometry. The angular distribution analysis further revealed the dependence of the power concentration on the incidence angle, which is essential for optimizing PV cell design. Although the current model was limited to a 2D axisymmetric representation, the results validate the concentrator's capability to enhance light collection and suggest promising perspectives for experimental realization. Future work could extend this study to include 3D modeling, thermal effects, and integration with advanced PV technologies. Overall, the Hamlet concentrator represents a viable and innovative approach to improving solar energy conversion efficiency.

ACKNOWLEDGMENTS

I would like to express my sincere gratitude to the University of Málaga for providing the technical support and access to the COMSOL Multiphysics software, which was essential for carrying out the simulations in this work. I am especially thankful to my supervisor, Professor Pedro Ángel Bernaola Galván, for his continuous guidance, encouragement, and valuable insights throughout the development of my master's thesis.

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