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Analysis and Simulation of CSP and Hybridized Systems

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Optical Design and Analysis of a Solar Crucible

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Abstract. A solar crucible was optically designed to be coupled with a Fresnel lens, which is a small-scale commercially available concentrator. To study the thermal aspects of the system, simple field experiments were conducted, and the results were used to set up a model. Finally, the designed crucible was analyzed using the developed model to evaluate its shape and behavior in vacuum or oxygen-free protected atmosphere.

Keywords: Solar Crucible, Optical Design, Thermal Analyses, Field Tests

1. Introduction

In order to significantly reduce CO_2 emissions and improve the security of energy supply, one of the strategies of the European Community is to replace hydrocarbons with hydrogen. This strategy presupposes, on the one hand, the adaptation of the structures currently dedicated to the storage and distribution of hydrocarbons and, on the other hand, the development of hydrogen production facilities.

Among the different scenarios taken into consideration, the techniques for the production of hydrogen with the exploitation of renewable energies, the so-called green hydrogen, deserve a deeper analysis. One of the renewable energies useful for the production of hydrogen is solar energy, in particular concentrated solar thermal energy, which allows to reach high temperatures.

Many articles describe methodologies to obtain temperatures between 1000 °C and 2000 °C through the concentration of solar energy [1-4]. In the literature, the works are oriented either to the use of large fields of heliostats or large solar collectors. These methodologies therefore allow the production of hydrogen for large-scale power plants. However, a little-studied area is the production of hydrogen on a small scale for use on unconnected islands or in isolated regions, as well as in small-scale artisanal sectors, such as goldsmithing, where hydrogen is already used for some processes. It has been shown that high temperatures can be achieved even by means of a small-scale array of solar collectors [4]. The volume in which the high temperature is reached is small, so the energy production is limited, but it could be sufficient in some areas such as those described above.

This research work aims to develop:

1) an optical study of a small-scale concentrator and the design of a solar crucible suitable for such a concentrator.

2) a thermal study of the receiver in order to estimate the temperature value in the crucible, its dimensions and the material to be used for its construction. Part of the study is dedicated to the identification of the most suitable shape of the crucible and its behavior under vacuum or in a protected atmosphere without air.

In a later phase, the model of the solar crucible will be validated by a field experiment.

2. Concentration of light

Suppose we have a concentration system as in Fig. 1.

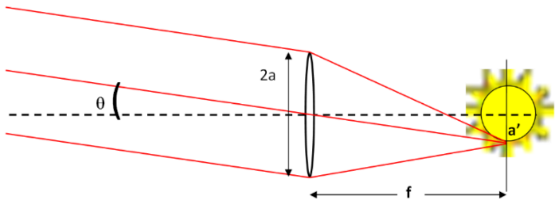

Figure 1. *Image of the sun on the receiver with a lens of focal length f and aperture diameter 2a*

The sun is concentrated by a lens of focal length *f*; the size *a*' (radius) of the solar image on the receiver placed in the focal plane is estimated with Eq. 1:

$$2a' = 2 \cdot f \cdot \tan\theta \qquad (1)$$

where *f* and θ represent the focal length of the lens and the solar divergence (semi-angle), respectively. The calculated value is slightly lower than the real one due to the aberrations of the lens.

In case the aperture *R* (radius) of a receiver is larger than the size of the image of the sun, it is possible to find a suitable position of the receiver, before or after the focus, where the aperture *R* of the receiver is uniformly illuminated.

Under these conditions, the irradiance at the receiver is described by Eq. 2:

$$IR = DNI * EL * (AL/AR) \qquad (2)$$

where *IR* is the irradiance at the receiver; *EL* is the lens efficiency; *AL* is the lens area; *AR* is the receiver area and *DNI* is the Direct Normal Irradiance. By choosing the lens characteristic and measuring the DNI, it is possible to calculate the *IR* at the receiver.

3. Experimental tests

Experimental tests were carried out at the INO facilities using a Fresnel lens concentrator to determine the temperature reached at the lens focus: the test set up is shown in Fig. 2.

Figure 2. *Photo of the test set up with the covered Fresnel lens mounted on the solar tracker*

A receiver made of refractory material was placed in the focus of the lens, and experimental tests were performed.

In these experimental tests, a metal target was placed in the focus of the lens. Some damage appeared at the points where the sunlight was concentrated.

In Fig. 3 the head of a steel screw is observed after an exposure of 120 seconds. The surface of the screw shows the effects of a metal fusion that should have occurred at a temperature between 1370 C° and 1536 C° (average temperature 1453 C°). The average value of the DNI during the exposure, measured with a pyranometer, was 801 W/m^2.

Figure 3. *A damaged steel screw after exposure, with a numerical ruler for size identification*

Considering that the area involved in the fusion has a diameter of about 11 mm, from Eq. 2 it can be calculated that the sample was irradiated with 2.46 MW/m^2. In this calculation the area of the lens is equal to 0.36 m^2.

4. Optical design of the solar crucible

To limit convection losses, it is necessary to work in the absence of air, so it will be necessary to make a crucible that allows the sample to be placed in an area where the air can be removed.

The characteristics of the crucible, illustrated below in Fig. 4, are designed to be coupled to the lens used for the preliminary tests.

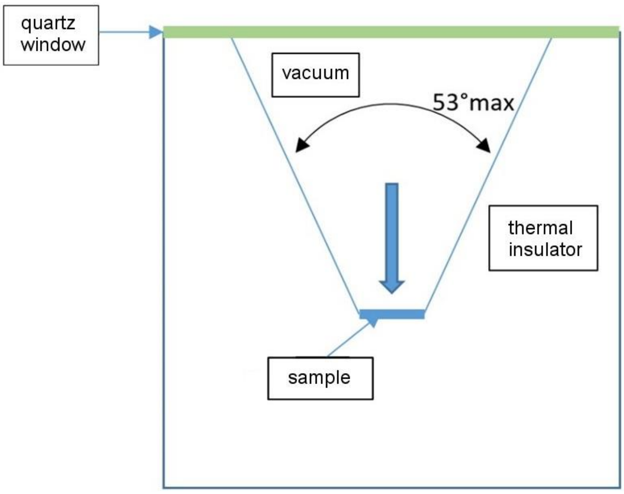

Figure 4. *Scheme of the solar crucible in section: the light enters from the upper quartz window and reaches the sample at the bottom of the crucible cavity; the crucible consists of a well of thermal insulating material. A vacuum was created in the cavity between the quartz window and the thermal insulation*

The light entering through the quartz window reaches the sample, which is placed at the bottom of the crucible cavity. The dimensions of the sample, a round disk, are 10 mm in diameter and 2 mm in thickness. The sample is supposed to be made of metallic material. The crucible material is assumed to be an insulating material.

5. Thermal simulations

COMSOL Multiphysics (CM for short) was used to perform thermal simulations.

The first simulation concerned the simulation of the experimental test (brick-screw) in order to validate the modeling choices, verifying the simulation results and calibrating the model. The geometry of the brick-screw model was created directly in CM. The screw was modelled as a cylinder. The materials used for the brick-screw model were: “Hf – 3 Zr” for the brick; “316” for the screw; “Air”. Regarding physics, the “Surface-to-Surface Radiation (rad)” and the “Heat Transfer in Solids and Fluids (ht)” were considered.

After the brick-screw simulation, the modeling and simulation of the solar crucible were performed; the experimental verification will take place, as previously mentioned, in a subsequent work. It was chosen to recreate the geometry of the solar crucible in CM by selecting “2D Axis-symmetric” as the “Space dimension”. In addition to the materials “Hf – 3 Zr”, “316” and “Air”, the material “Glass” was also used and the physical quantity “Single-Phase Flow-Laminar Flow” was examined to consider the effect of the air in the cavity.

5.1 Simulation of the experimental test

The 3D model of the brick with the cylinder, created directly in CM, is visible in Fig. 5.

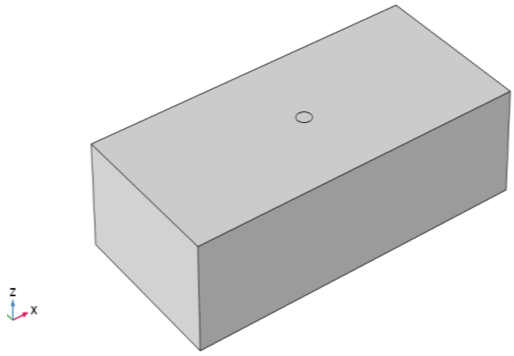

Figure 5. *Cylinder-brick system, representing the experimental test, as simulated in CM*

The dimensions of the brick are 240x120x60 mm^3, while the diameter of the cylinder is 11 mm as in the previous experimental tests.

The characteristics of the brick and the cylinder respectively are as follows:

Brick:

- Material: Brick
- Emissivity: 0.75
- Thermal conductivity: 1.8 [W/(m*K)]
- Specific heat of mass: 900 [J/(kg*K)]
- Density: 2000 [kg/m^3]

Cylinder:

- Material: Iron alloys 316
- Emissivity: 0.89

The results of the simulation of the system by varying the height of the cylinder reproducing the screw are shown in Table 1 and Fig. 6. It can be observed that we are approximately at the temperature estimated for the experiment concerning the metal screw. Table 1 reports the received irradiance and the maximum temperature (reached after 120 seconds, as per experimental test).

Table 1. *Simulation results as the screw (cylinder) height varies.*

Screw height [mm]	Irradiance [MW/m^2]	T_{MAX} [°C]
2	2.4	1800
4	2.4	1650
6	2.4	1560
8	2.4	1470
10	2.4	1410

Fig. 6 represents the simulated case with screw height 2 mm. It can be observed that the temperatures are higher near the spot, in agreement with the physics of the problem.

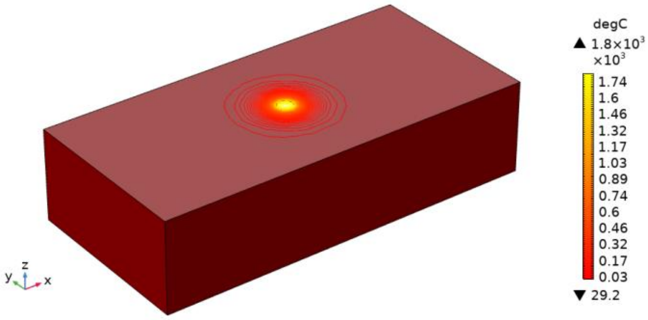

Figure 6. *Simulation result for the cylinder-brick system in CM (screw height 2 mm)*

The values in Table 1 are those at steady state, but the simulation was dynamic for a duration of 120 seconds, as per the experimental test. Fig. 7 shows the simulation results as time increases and height varies; the height parameter refers to the length of the cylinder, as reported in column 1 of Table 1.

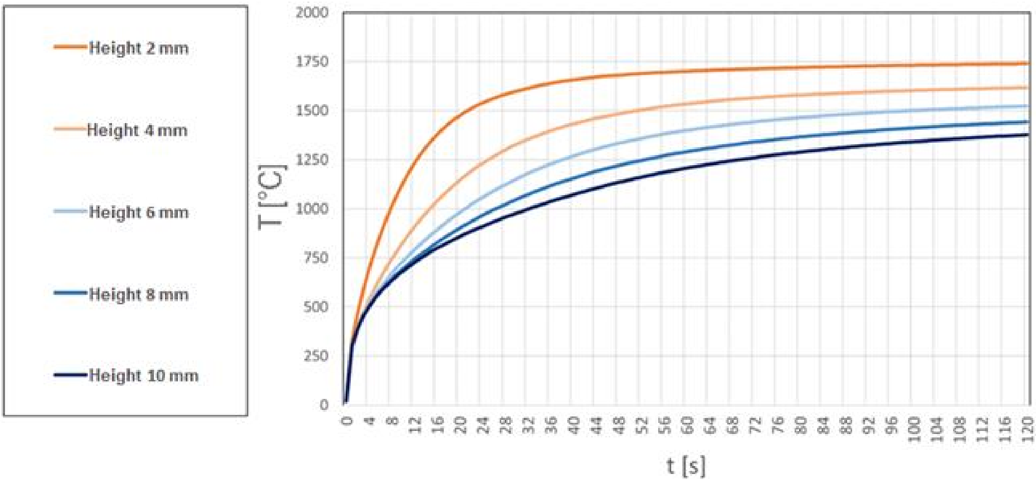

Figure 7. *Transient simulation results: the brick temperature is plotted as a function of time for different heights, which correspond to the lengths of the cylinder*

In Fig. 7 it can be observed how the temperature increases during the time-dependent simulation. The temperature increase is less rapid as the height of the cylinder (screw) increases. The highest temperature values are obtained for the cylinder with the smallest height. The results are consistent with the physics of the problem. In combination with the maximum temperature value obtained at steady state, compared to the experimental one, we consider the model valid and therefore usable for predictions.

5.2 Crucible simulation

Subsequently, CAD models of the solar crucible and its container were created in SolidWorks (Fig. 8). However, to reduce the calculation time, it was decided to recreate the system geometry in CM, choosing “2D Axis-symmetric” as the “Space dimension”. Fig. 8 shows the CAD model of the solar crucible (side a) and the CAD model of the solar crucible container (side b): for both, a ¾ top view and a central section are shown.

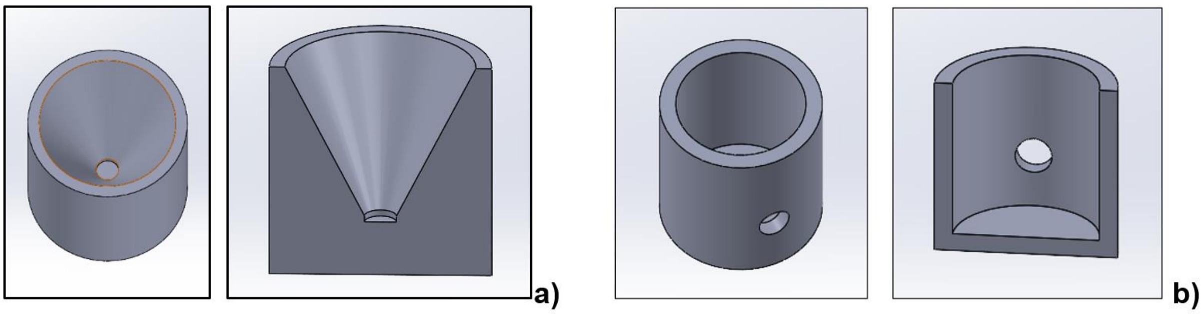

Figure 8. *a) CAD model of the solar crucible, created in SolidWorks; b) CAD model of the solar crucible container, created in SolidWorks*

The characteristics of the CAD model of the crucible and its container are as follows:

Crucible:

- Outer diameter: 70 mm;
- Internal diameter: 60 mm;
- Height: 70 mm;
- Opening angle: 53°;
- Diameter of the spot: 10 mm;
- Height of the spot: 2 mm.

Container:

- External diameter: 200 mm;
- Internal diameter: 160 mm;
- External height: 200 mm;
- Internal height: 180 mm.

Table 2 reports the values of maximum temperature reached in the crucible (T_{MAX}), calculated both in the presence of air in the crucible and in the presence of a vacuum created in the crucible. As the diameter of the irradiated area (spot diameter) varies, the average irradiance also varies. An input irradiance on the lens of 800 W/m^2 was considered. As it can be seen, the difference in the maximum temperature achievable under the same conditions makes it clear that it is worth adding the complication of creating a vacuum inside the crucible to reach higher temperatures.

Table 2. *Simulation results varying the diameter of the spot.*

Spot diameter [mm]	Irradiance [MW/m^2]	T_{MAX} Air [°C]	T_{MAX} Vacuum [°C]
5	11.92	3030	5430
10	2.98	1940	2950
15	1.32	1450	1960
20	0.74	1150	1430
25	0.48	948	1120

An example of a result obtained in CM is shown in Fig. 9. The complete model of the solar crucible can be observed: the solar crucible (composed of the quartz window, the cavity, the sample and the thermal insulator) inside its container. As for the brick-screw simulation, the temperatures are higher near the spot, so the simulation is consistent with the physics of the problem.

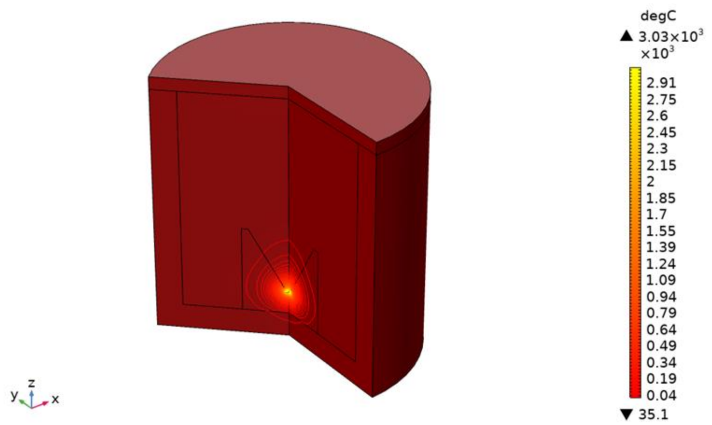

Figure 9. *Simulation result of the crucible and its container in CM*

As regards the brick case, the above values are those at steady state, but the simulation was carried out in transient state and for a time of 120 seconds for both air and vacuum.

6. Conclusions

The aim of this research was to design a solar crucible, coupled with a Fresnel lens. To achieve this goal, several phases were performed:

- The first step was the optical study of a solar crucible suitable for a Fresnel lens, which is a small-sized and commercially available concentrator.
- The second step was the realization of some simple experiments to evaluate the level of power concentrated in the system focus in real conditions.
- The third step was the construction and validation of a model for thermal studies based on the results obtained in the second step, so that it can be used for predictions.
- The fourth step was the analysis of the crucible designed using the developed model in order to estimate the value of the temperature inside it, both in the presence of air and under vacuum, its dimensions and the material to be used for its construction.

Future improvements of the experimental work will consist in validation employing a realized crucible.

Data availability statement

The data are available on request.

Author contributions

Author Contributions: Paola Sansoni (Visualization, Formal Analysis, Writing – review & editing); Daniela Fontani (Conceptualization, Methodology, Visualization, Writing – original draft); Franco Francini (Conceptualization, Formal Analysis); Maurizio De Lucia (Supervision, Validation); Emanuele Giusti (Methodology, Visualization, Writing – original draft, Data curation); David Jafrancesco (Validation, Data curation).

Competing interests

The authors declare no competing interests.

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References

[1] K. Hatakeyama, H. Kaneko, and K. Nishioka “Formation of Silicon from Shirasu Volcanic Ash Using Solar Furnace.” International Journal of Materials, Mechanics and Manufacturing, Vol. 4, No. 2, May 2016. DOI: 10.7763/IJMMM.2016.V4.245
[2] N. Zhao, J. Wang “Solar full spectrum management in low and medium temperature light-driven chemical hydrogen synthesis - A review.“ Renewable and Sustainable Energy Reviews, vol. 196, pp. 114368, 2024, https://doi.org/10.1016/j.rser.2024.114368.
[3] B. A.G. Bossink “Demonstrating sustainable energy: A review based model of sustainable energy demonstration projects, Renewable and Sustainable Energy Reviews, vol. 77, pp.1349-1362, 2017, https://doi.org/10.1016/j.rser.2017.02.002.
[4] A. Radwan, M. A. Abdelkareem, B.A.A. Yousef, A.G. Olabi, “Solar thermal energy applications” in Renewable Energy, Vol.1: Solar, Wind, and Hydropower, Academic Press, 2023, Chapter 1.3, pp. 45-74, https://doi.org/10.1016/B978-0-323-99568-9.00005-4.