Etude expérimentale et théorique d'un métamatériaux concentrateur thermique

Experimental-theoretical investigation of a metamaterial thermal concentrator

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Résumé - Cet article présente une analyse expérimentale et théorique d'un concentrateur thermique pouvant être modélisé comme un métamatériau thermique. La conception de ce concentrateur s'inspire de la récupération d'énergie à partir du panneau arrière d'un système photovoltaïque à haute concentration (HCPV), permettant la collecte simultanée de la chaleur provenant de quatre sources thermiques. Un dispositif expérimental intégrant des mesures de thermographie infrarouge a été mis au point. Les résultats expérimentaux sont comparés à des simulations numériques afin d'optimiser la conception du dispositif.

Abstract - The present paper provides an experimental-theoretical analysis of a thermal concentrator that can be represented as a thermal metamaterial. The concentrator design was motivated by the energy harvesting from the back panel of a high concentration photovoltaic system (HCPV), allowing the simultaneous heat collection from four thermal sources. An experimental setup incorporating infrared thermography measurements was developed. The experimental results are compared with numerical simulations to optimize the device design.

1. Introduction

Metamaterials can be defined as high-performance functional materials that are designed to have artificial effective physical properties, combining natural materials in different geometries, arrangements, and dimensions. The last two decades have seen breakthroughs in this field and this accumulated understanding and available design and manufacturing tools begin to effectively deliver solutions in different physical areas. As part of this wider trend, the so called thermal metamaterials have been proposed in different contexts, aiming to control heat flow through the proper design of engineered materials with desirable effective thermophysical properties is essential in shielding or altering thermal signatures and in enhancing thermal energy sustainability through harvesting and efficiency improvement [1-4]. One main example of the use of metamaterials in thermal management will be here considered, namely thermal concentrators, which focus heat flow from different sources into a smaller area. Different

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geometries have been theoretically analysed and experimentally demonstrated, including some fairly simple flower-shaped fin configurations [5-12].

A crucial step in the development of a specific thermal metamaterial involves modelling the modified physical properties through transformational optics and simulating various geometries and arrangements of such heterogeneous anisotropic media, with the corresponding complex spatially variable patterns incorporated into the variable anisotropic properties, as discussed in [13-14] for a thermal cloak illustration. However, in some simpler geometric configurations, it is still possible to simulate the detailed multi-region and multi-media arrangement through classical heat transfer theory, without recurring to the transformational optics reformulation. The present work thus provides an experimental-theoretical analysis of a relatively simple manufactured thermal concentrator based on previously published thermal metamaterial designs, motivated by an application in waste heat recovery from high concentration photovoltaic (HCPV) panels [15-16]. Each individual photovoltaic cell is associated with a Fresnel lens for radiation concentration, which leads to a considerable heat dissipation to the HCPV structure. Nevertheless, the aluminium back panel of the HCPV system is sufficiently effective in passively removing and exchanging heat with the external ambient. However, it remains of interest to recover this waste heat and use it for a secondary process, such as membrane distillation for water desalination, which has been proposed in [15-16]. The solution involves the thermohydraulic design, 3D printing and installation of micro heat exchangers to the back of each photovoltaic cell. The aim of the present exploratory design of a thermal concentrator is to reduce the number of micro-heat exchangers required to recover the thermal energy from the HCPV system back panel, through the use of fairly simple thermal concentrators located in the central position with respect to every four photovoltaic cells, thus reducing the number of micro-thermal devices by a factor of four once sufficient concentration is achieved.

2. Experimental analysis

The objective of the experimental analysis is acquiring reliable data for the thermal behaviour of a proposed thermal concentrator in order to use it as a heat harvesting device on a HCPV (High Concentration Photovoltaic) solar system whose heat losses are partially recovered through the use of micro-heat exchangers, attached to the back of the photovoltaic cells, on the surface of the HCPV system metallic back panel. A flower-shaped thermal concentrator metamaterial was chosen, which encodes several physically meaningful design advantages for capturing and focusing waste heat [6,11]. The present configuration deals only with isotropic materials but can be improved if paired with anisotropic or spatially graded materials.

The thermal concentrator studied (Fig. 1) consists of a composite structure made up of a polydimethylsiloxane (PDMS) disk into which a central copper piece is integrated. This piece (Fig. 2) is designed as a conductive element with radial fins extending towards the periphery of the disk. The architecture of the device aims to exploit the marked contrast in thermal conductivity between PDMS, a poorly conductive and therefore insulating material, and copper, a highly conductive material. The combination of PDMS and copper, in combination with an adequate fin geometry, promotes the orientation of the heat fluxes and constitutes an innovative approach in the field of thermal metamaterials [17].

The copper component (Fig. 2) plays a central role in the functioning of the metamaterial. The fins ensure the efficient collection of heat generated at the ends of the metal plate, while the central part of the copper component is designed to concentrate the recovered heat. This geometric configuration thus preferentially guides heat flow from the periphery, where heat is lost, towards the central area of the device. Thanks to this design, the metamaterial acts as a passive heat concentrator, allowing for a controlled redistribution of heat flow and a localized temperature increase at the central zone of the device. This principle opens up interesting possibilities for applications in thermal management, energy storage, and heat recovery systems [18].

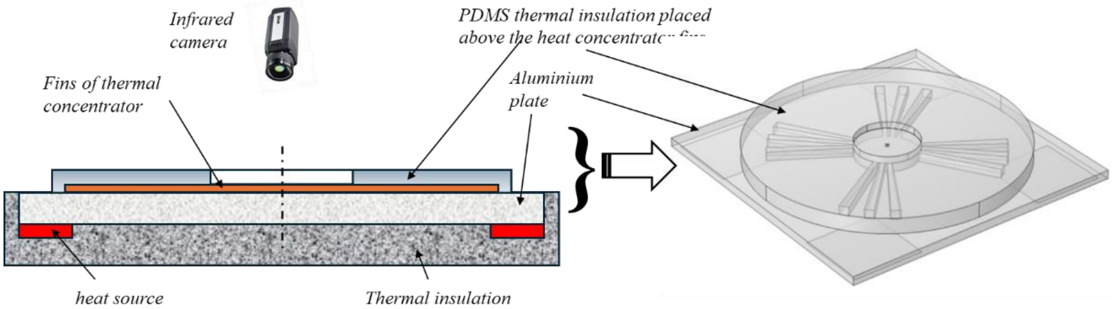
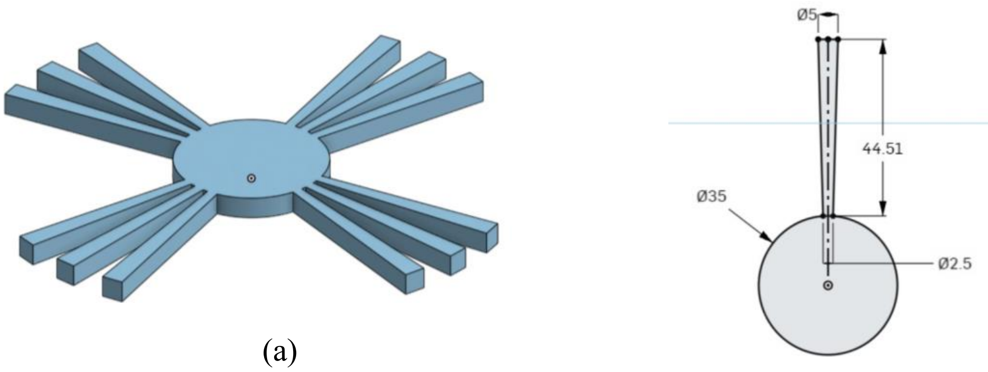


Figure 1: *Presentation of the different elements of the experimental setup.*

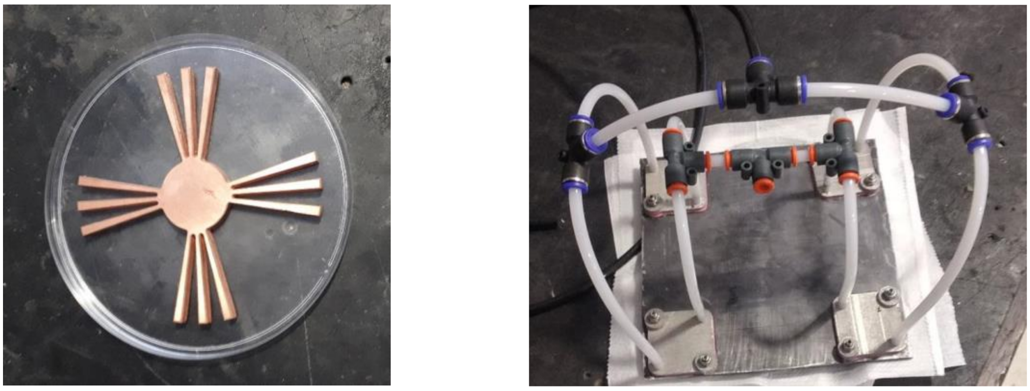


(a) (b)

Figure 2: *Presentation of the central part of the copper concentrator (a) and its dimensions (b).*

The aluminium base is a square piece measuring 160 mm on each side (Fig. 1), which is subjected to the heat fluxes generated by the four heat sources. Their geometry is represented by the four surfaces located at the four corners of the square base of the plate. Insulation is used to limit heat losses. This insulation with PDMS material consists of a 150 mm foam cylinder with a cylindrical opening providing access to the central surface of the copper star. The central zone of the metamaterial is formed by a central disk 35 mm in diameter, on which are distributed fins 44.51 mm long, with a width of 2.5 mm at its narrowest point and 5 mm at its widest. Figure 3a show the final configuration of the PDMS-Copper thermal concentrator, while Fig. 3b illustrates the base aluminium plate with the four micro-heat exchangers installed as heat sources, once connected to the thermal bath.

For temperature measurements on the back side of the thermal concentrator, the FLIR SC645 infrared thermography camera is used, which performs non-contact measurements and allows thermograms to be generated as needed on the entire back surface of the metamaterial. The upper surface of the system in front of the camera is painted black with a paint of emissivity equal to 98%.



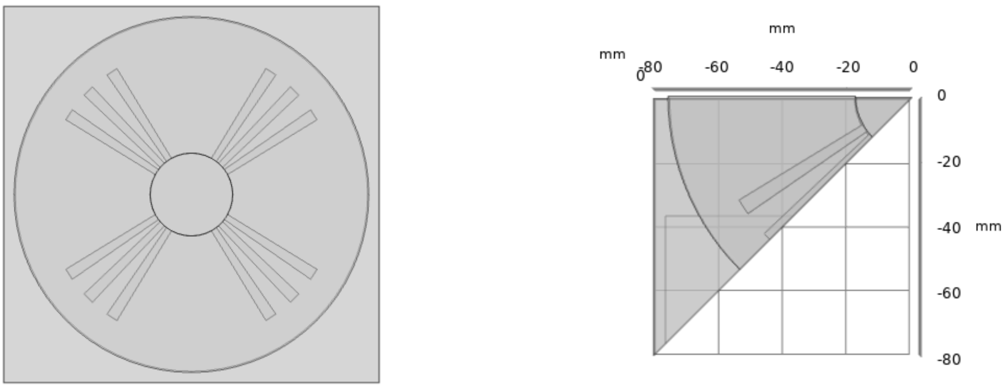
(a) Final configuration of thermal concentrator

(b) Setup of base plate with heaters (micro-heat exchangers)

Figure 3: *Details of the thermal concentrator and of the aluminium base with heat sources.*

3. Theoretical analysis

To numerically investigate the performance of the heat concentrator, a three-dimensional model was developed using COMSOL Multiphysics, through the conduction heat transfer module. The main objective of this simulation is to reproduce the redistribution of heat flow promoted by the copper fins embedded in the PDMS matrix, replicating the conditions of the experiment. The modelled geometry consists of a cylindrical sector composed of copper fins arranged radially within a PDMS matrix, both supported on an aluminium plate that acts as a base where heat sources were positioned. All dimensions, as well as the positioning of the heat exchangers, were determined according to the experimental arrangement. Aiming to optimize simulation time, it was possible to simplify the model by exploiting its radial symmetry. Observing that the device can be divided into eight equal parts, subsequent calculations were performed using only one-eighth of the geometry (Figure 4b). This simplification drastically reduced the computational time required, without compromising the accuracy of the results, and allowed the use of more refined meshes.



(a) Original configuration

(b) Reduced symmetric configuration

Figure 4: *Top view of the geometries, original and simplified by radial symmetry (one eighth of the device).*

A crucial step in the mathematical modelling of the thermal concentrator is the careful definition of the boundary conditions, which represent the heat exchanges between the system and the environment. In this context, it was necessary to model two main thermal interactions between the metamaterial and the environment: the heat supply by the photovoltaic cells, represented in the experiment by four micro heat exchangers, and the heat loss through the surfaces to the air by natural convection and radiation. COMSOL includes a built-in feature to compute heat transfer coefficients that accounts for both spatial and temporal temperature variations. Instead of assuming a constant value, it evaluates the coefficient locally, adapting to changes in temperature across the domain and over time, thereby capturing transient and non-uniform thermal effects more accurately. Different approaches were considered to model the coupling with the heat exchangers. Initially, we employed a prescribed heat flux condition, using a parametric sweep to identify the most appropriate value, and later also allowed for the convective coupling with an estimated internal heat transfer coefficient for the micro-heat exchangers. Additionally, considering the presence of heat transfer between solids composed of different materials, it is imperative to focus on the conditions of thermal transfer at the interfaces between these materials. In the present phase of the project, we have estimated a thermal contact conductance coefficient between the micro heat exchanger surface and the aluminium plate, with the thermal paste utilized, of approximately 245 W/m².K.

4. Results and discussion

Figure 5 below shows an example of acquisition of the experimental measurements made by the infrared thermography camera as shown schematically in Figure 4 and explained in paragraph 2. The thermogram also shows tree crossed temperature lines (01,02,03) located on the back side of the concentrator, one representing a vertical line (line01) that runs mostly along the PDMS region while the diagonal ones (lines 2,3) runs along the finned area. As can be seen in the image at the bottom right, the initial results clearly show that the temperature in the central zone is higher than that in the rest of the concentrator, which demonstrates that the proposed metamaterial plays its role in concentrating the heat flux to the selected area. Furthermore, the temperature along the fins is higher than that in the finless areas. In this example the water temperature was controlled in the thermal bath at 40 C and the central point reaches 37,1 C.

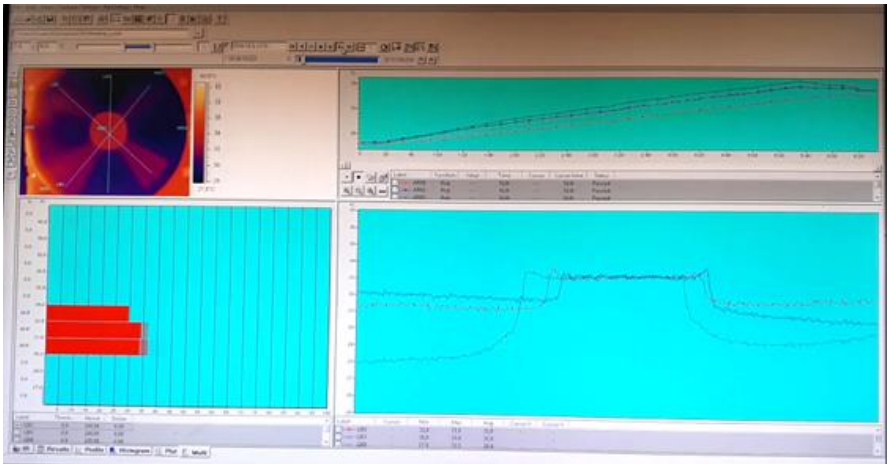


Figure 5: A thermogram taken by the infrared thermography camera on the upper face with representation of the experimental setup of the heat recovery system with these different elements.

As for the simulation, figure 6 illustrates the automatic meshing provided by the COMSOL platform, for the considered reduced domain, in the Extra Fine option. After a mesh refinement analysis, by selecting the increasing refined meshes (Normal, Fine, Finer, Extra Fine and Extremely Fine) the option Extra Fined was considered sufficiently accurate and selected for reporting the comparative results that follow.

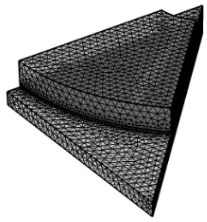


Figure 6: *Example of the mesh generated by the COMSOL software for Extra Fine selection.*

To test the imposed heat flux condition at the sources in the numerical model, we used different heat flux shapes and variations to verify that the model accurately accounts for this condition. Figure 7 shows the comparison between experimental and theoretical results for the temperature measured at the surface of the central zone of the copper concentrator, under transient conditions, for a controlled water bath temperature of 45 °C. The experimental data used are represented by blue dots, while the theoretical results for the two boundary conditions considered are represented in orange (imposed heat flux) and green (convective heat transfer). The imposed heat flux, obtained using the COMSOL fitting procedure, shows better agreement with the experimental results but overestimates the central temperature peak. This is due to the small variation in the imposed heat flux, in contrast to the more gradual variation in the temperature of the water circulating in the micro heat exchangers. Regarding the convective boundary condition proposed by COMSOL, imposing a constant heat transfer coefficient and water temperature does not correspond to physical reality, and a more complete model of the micro heat exchanger will need to be developed if necessary. Therefore, we used the constant imposed heat flux condition in the comparison of the different forms of the heat concentrator presented in the following paragraph.

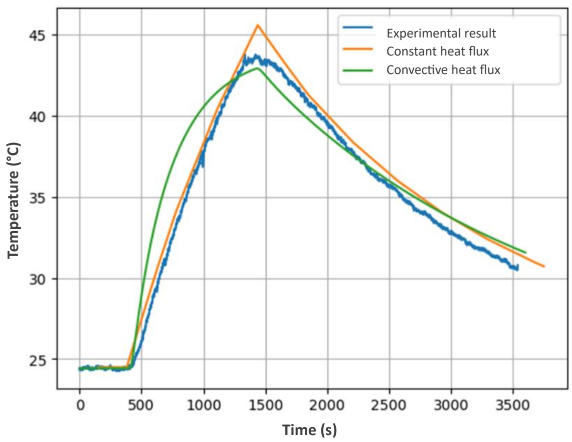
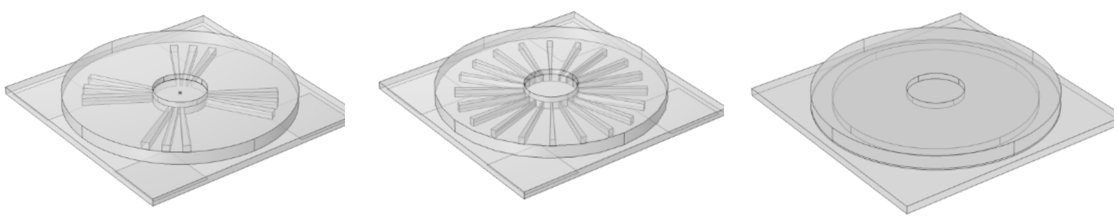
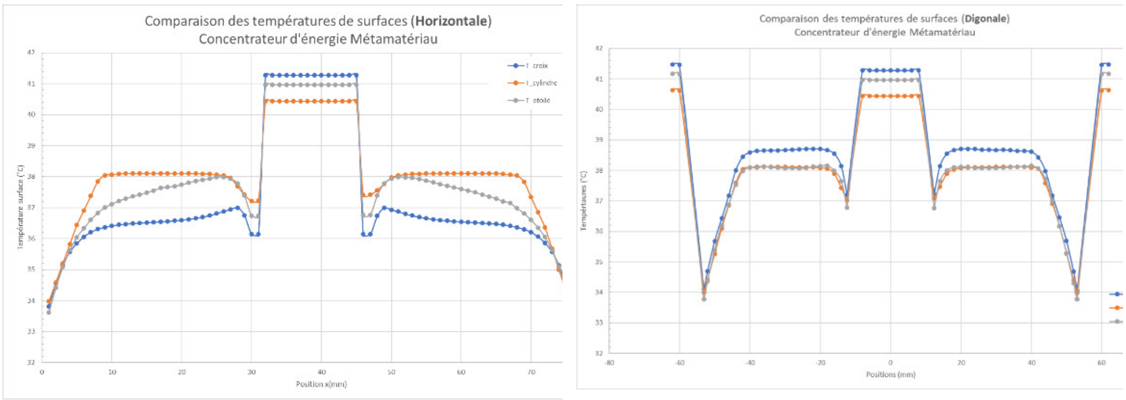


Figure 7: *Comparison of experimental (blue) and theoretical results for two different boundary conditions – prescribed heat flux (orange) and convective heat transfer (green).*



(a) Cross-like fins (b) Star-like fins (c) Full circle

Figure 8: *Different tested configurations of thermal concentrators*



(a) Temperatures along horizontal line (b) Temperatures along diagonal line

Figure 9: *Temperature distributions along horizontal and diagonal lines for the different tested configurations of thermal concentrators*

To illustrate the capabilities of the simulation tool here implemented, three different arrangements of fins were considered aiming at comparing their thermal behaviours in the concentration purpose, namely, the proposed cross-like arrangement of fins, a star-like equally spaced fins set, and a full copper circle (Figure 8). Figure 9 shows the results of COMSOL simulations where it appears that the cross configuration offers the most efficient concentration effect, as evidenced by the highest temperature readings reached along the fins and especially in the central circular area. This central area will be the most suitable for heat recovery.

5. Conclusions

The present work offers a comprehensive experimental and theoretical investigation of a thermal concentrator proposed for energy harvesting across a range of thermal management applications. It examines both the physical behavior and a modelling strategy based on CFD (COMSOL), providing insights into performance of configuration variations under realistic operating conditions. A key aspect addressed is the need for proper formulation of transient boundary conditions, which is essential for accurately simulating these devices, particularly when modelling their dynamic interaction with heat sources. Careful treatment of this coupling is shown to be critical for capturing the temporal evolution of heat transfer and ensuring reliable predictive results. For the relatively simple cross-shaped thermal concentrator, it was verified that a direct computational simulation of the heterogeneous material was sufficiently accurate to reproduce the experimental behavior, thus not requiring the transformational optics treatment that is in general applied to metamaterial analysis. Although, in our case, the dimensions involved in the design of the metamaterial are large enough that resolving the phenomena requires the use of classical numerical simulation based on the formulation of a heterogeneous medium, future work should address the transformational optics alternative for critical comparisons between the models. In principle, the metamaterial optimization task should be more efficiently accomplished in the framework of the compact transformational diffusion formulation.

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