Thermal Performance Analysis of Non-Vacuum Receivers for Linear Fresnel Systems: CFD modelling versus Experimental Insights

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***Abstract*—Optimizing the performance of The Linear Fresnel CSP system typically relies on two complementary approaches. The first involves analyzing the optical interactions between solar radiation and the system's various components. This analysis is then coupled with a thermal modelling to assess the overall performance of the installation. In this study, numerical simulations of heat transfer within the air cavity were performed to develop a tool for evaluating thermal losses and optimizing the receiver design. We present a methodology for measuring the system's overall performance by combining the Monte Carlo Ray-Tracing method with a CFD approach. The optical analysis is carried out using the OPSOL ray-tracing code, while the thermal analysis is conducted with ANSYS-Fluent software. It is concluded that the proposed methodology serves as an effective substitute for experimental approaches in characterizing the receiver's thermal performance.**

***Keywords*—Monte Carlo method; Ray-Tracing; CFD modelling; Linear Fresnel Receiver; Heat losses; experimental assessment;**

I. INTRODUCTION

In recent years, Linear Fresnel concentrator (LFC) systems have emerged as one of the most promising technologies for concentrated solar power (CSP) plants, mainly due to their thermal efficiency and cost-effectiveness. The simplicity of this technology makes it adaptable to a wide range of environments, offering significant potential for widespread adoption. However, despite these advantages, the understanding and development of LFC systems remain limited, as relatively few industrial-scale plants are currently operational.

When compared to parabolic trough concentrators (PTCs), LFC systems are particularly well-suited for process heat applications and offer several key benefits, including technological simplicity and reduced land usage [1]. Furthermore, their potential to address current CSP challenges, such as simplifying construction processes and reducing costs, has been recognized. LFC systems are efficient within the medium-temperature range of 100–250°C, where they can produce both saturated and superheated steam[2]. These advantages make LFC systems applicable across various industrial processes, including enhanced oil recovery (EOR), cooling, agro-food processing, water desalination, and chemical manufacturing [3].

LFC systems utilize a linear focusing mechanism to generate electricity and providing thermal energy for industrial applications. A typical system consists of two main components: a field of flat or slightly curved mirrors, and a receiver system. Together, these components constitute the solar field, where solar radiation is concentrated and converted into heat within the receiver.

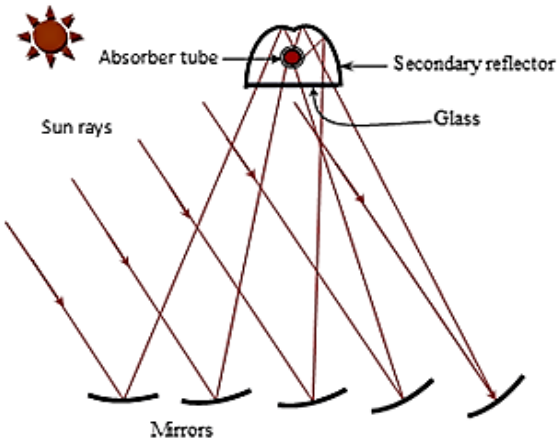

Fig. 1. Sketch of linear Fresnel Concentrator

One of the key advantages of LFC systems over PTCs lies in

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their fixed receiver design, which offers greater flexibility for technical and economic optimization. This flexibility allows for the integration of non-vacuum receivers, which consist of an absorber tube, a compound parabolic reflector as a secondary reflector, and a transparent cover. Unlike the vacuum tube receivers commonly used in PTC systems, non-vacuum receivers are simpler to manufacture and provide additional development opportunities.

This receiver studied here was designed and optimized in the framework of Sirocco Project [4]. To enhance the overall performance of LFC systems, we propose an analysis of heat transfer processes within the receiver where Computational Fluid Dynamics (CFD) methods is combined with Monte Carlo ray-tracing techniques. These approaches enable accurate predictions of receiver performance under steady-state conditions by simulating bouth otptical interaction and detailed heat-mass transfer phenomena.

II. RAY-TRACING MODEL

Before conducting the thermal analysis, it is essential to evaluate the heat fluxes intercepted by the various components of the receiver. These fluxes can then be used as boundary conditions in the thermal model. Although this approach may seem intuitive, it is important to highlight certain details that could affect the results. Indeed, the optical calculation not only determines the optical efficiency of the concentrator, but also quantifies the total heat flux intercepted by the absorber tube, which serves as the final destination of the solar radiations. Furthermore, our approach teak into account the fraction of solar radiation absorbed by the glass cover and the secondary reflector, since these components cannot be considered as perfect transmitters or reflectors from an optical viewpoint.

The 3D optical modeling of the Fresnel concentrator is based on Monte Carlo method combined with a ray-tracing algorithm. The simulations were performed using the optical simulation environment OPSOL [4] (figure 2).

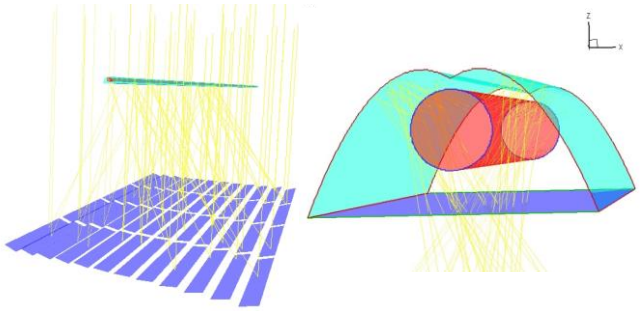

Fig. 2. Simulation of the optical interactions between sunrays and different LFR optical components using OPSOL code

Figures 3 and 4 show the simulation results over the course of a day, in terms of the overall optical efficiency (Figure 3) and the corresponding powers including the useful heat flux and the optical losses (Figure 4).

It can be seen that the useful absorbed solar heat flux by the absorber tube is an intermittent quantity. However, it can be considered as a constant parameter during a period between 9 h and 16 h (figure 5) despite the systematic variation of the DNI. The fluctuations observed during the same period are mainly caused by the passage of the receiver's shadow between the rows of mirrors and the gaps separating them.

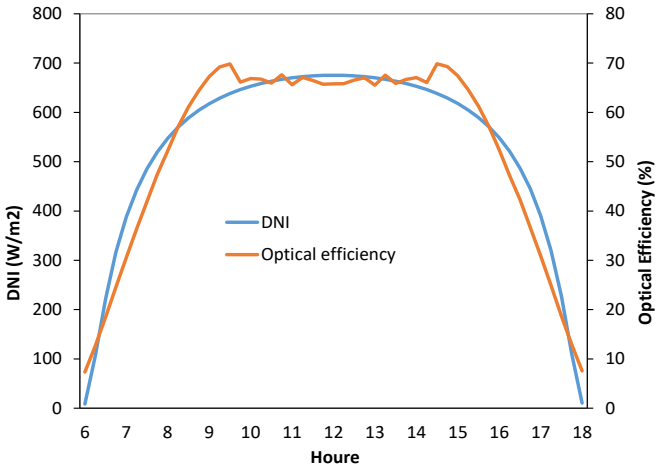

Fig. 3. Daily evolution of optical efficiency of the linear Fresnel concentrator

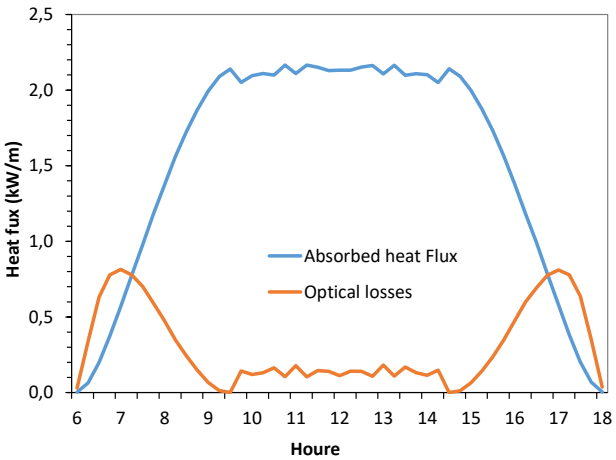

Fig. 4. Daily evolution of the heat flux absorbed by the absorber tube and optical losses

III. CFD MODEL OF THE RECEIVER CAVITY

Inside the air cavity, A mutual heat exchange occurs between the cavity components by convection and radiation. the incompressible Navier-Stokes equations for Newtonian fluid with constant physical properties are considered. The Boussinesq approximation is adopted to account for the density variations due to temperature difference. Under these assumptions, the governing equations in the dimensionless form are:

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$$\nabla . u = 0 \quad (1)$$

$$\frac{\partial u}{\partial t} + (u.\nabla)u = \Pr Ra^{-1/2}\nabla^2 u - \nabla p + f \quad (2)$$

$$\frac{\partial T}{\partial t} + (u.\nabla)T = Ra^{-1/2}\nabla^2 T \quad (3)$$

where u is the velocity vector, t the time, p the pressure, T the temperature. The numerical resolution of the governing equation is based on the finite volume method. Therefore, the domain is subdivided into a number of cells and the conservation equations are discretized and solved using the SIMPLE algorithm. Surface-to-Surface Radiation approach is used to simulate heat transfer by radiation where all surfaces are considered as gray bodies.

The results of the optical calculations expressed in terms of solar power absorbed by the absorber tube, the secondary reflector, and the glass cover, are used as boundary conditions in the CFD model. The thermal simulation conducted based on Ansys-Fluent enables the determination of the temperature distribution within each component of the receiver.

Figure 5 present an example of CFD simulation results for temperatures and velocity fields inside the air cavity.

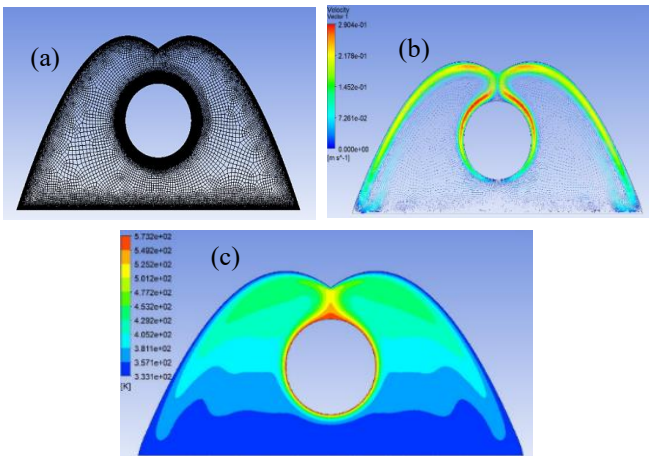

Fig. 5. Discretization of the calculation domain using quadratic elements (a), air velocities (b) and Temperature (c) fields.

IV. Experimental Appraoch

The CFD model is validated by numerically replicating the experimental conditions applied to a 2-meter prototype, including real cross-sectional dimensions, which was designed and constructed in laboratory. More details about the experimental procedure can be found in a previous work referenced in [5]. To calculate the receiver's total thermal losses toward the external medium, repeated simulations was performed by varying the absorber tube temperature, considered as boundary condition in thermal model.

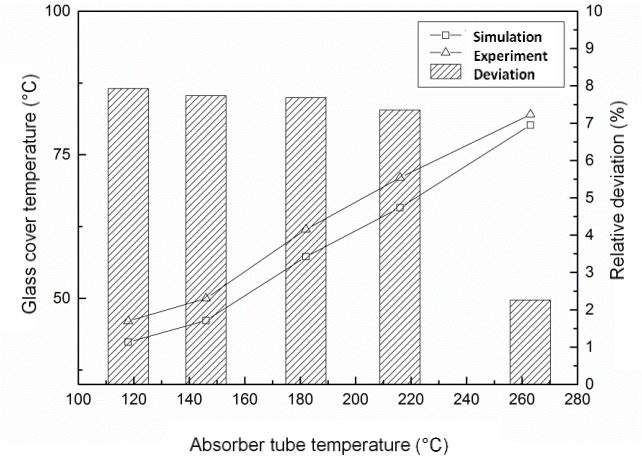

Fig. 6. Glass cover temperature according to absorber tube temperature: comparison between CFD model and experiment

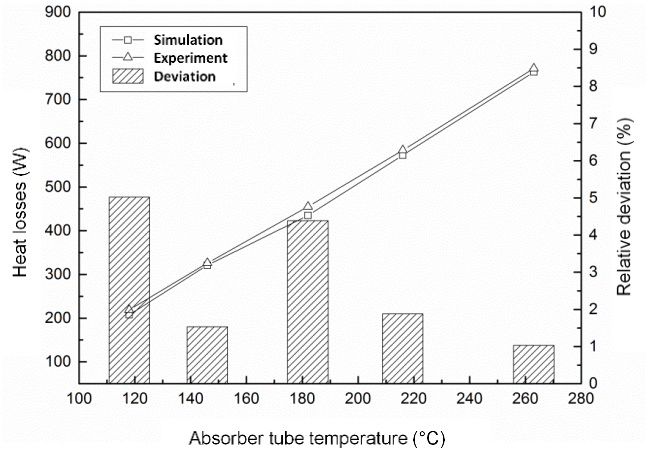

Fig. 7. Receiver heat losses according to absorber tube temperature: comparison between CFD model and experiment

Figures 4 and 5 illustrates a comparison between the experimental data and the CFD model results focusing on overall heat losses and the average temperature of the glass cover. The average relative deviation for temperatures is approximately 8% (Figure 6). These systematic deviations are mainly due to the significant temperature inhomogeneity, which affects the calculation of the average representative, temperature for each surface, while during experiment only average temperatures are considered. However, the key finding relates to the overall heat losses. As shown in Figure 7, for absorber tube temperatures ranging from 120 to 280°C; the average relative deviation between the measured thermal losses and those predicted by the model does not exceed 6%. This result demonstrates that the proposed method accurately

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reproduces the global heat balance within an acceptable margin of error. Therefore, the proposed model is determined to be a reliable and efficient alternative to experimental methods.

V. CONCLUSION

This work describes a methodology for numerical assessment of thermal performance of no vacuum tube CPC type receiver for linear Fresnel system. The proposed approach consisted in combining the Monte Carlo/Ray tracing method with detailed CFD model. An experimental prototype was used to validate the numerical model. The comparison between both experimental and numerical results showed that the proposed approach could be used with reasonable confidence to evaluate the receiver thermal performances. Consequently, the proposed methodology is considered a reliable and efficient alternative to experimental methods for accurately characterizing the thermal performance of the receiver.

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