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Analysis of the performance of linear Fresnel collectors: Encapsulated vs. evacuated tubes

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ABSTRACT

In order to reduce the cost of the produced electricity, the Linear Fresnel Collector (LFC) system is a promising Concentrated Solar Power (CSP) technology. In this paper a detailed study is conducted aimed at the assessment of the heat losses from the receiver of a real 1 MWe pilot plant based on the Fresnel collector and cooled with a thermal oil. The receiver unit, which consists of an absorber tube and a compound parabolic concentrator (CPC), is investigated numerically in order to determine the receiver performance in different wind directions. Two receiver configurations are analyzed: a simply encapsulated one and an evacuated one. In the latter case, high vacuum conditions are reached in the gap between the absorber tube and the glass cover, whereas in the former case, air at ambient pressure fills the gap. The spatial distribution of the heat flux absorbed by the absorber tube and by the glass cover is determined by means of an optical analysis, conducted with the Monte Carlo based open-source ray-tracing tool Tonatiuh, and it is the driver of the ensuing thermal fluid dynamic analysis. A reference operation condition is studied in detail by means of a 1D model that solves the energy balance for the coolant along the entire length of the receiver. The characterization of the 1D model requires an accurate, multi-dimensional computational fluid dynamic (CFD) analysis, based on the commercial STAR-CCM+ code, which aims at determining the useful heat transferred to the coolant and the convective and radiative heat losses as a function of the oil temperature. A 2D CFD model is used to simulate the thermal behavior of the receiver at different locations along its axis in case of no wind or wind blowing across the collector axis. A 3D CFD model is adopted to study the impact of the wind blowing along the collector axis. The external air is considered in the computational domain in both CFD models, to be able to accurately assess the convective share of the heat losses. At the end, the oil temperature profile along the receiver tube, as well as the heat losses and the thermal efficiency trends, are presented and discussed. The 2D model is also exploited to perform an annual analysis, varying the solar flux and the sun position, but considering just a single wind direction. The results of our analysis indicate that the benefit of using an evacuated tube depends on the heat absorbed on the linear receiver, which depends in turn on the solar flux and on the sun position. The annual-based performance improvement obtained using an evacuated tube is not dramatic, due to the relatively low temperatures of the receiver. Moreover, this analysis also concludes that the receiver performance is only slightly affected by the wind direction and intensity up to ~ 4 m/s, due to the presence of the CPC that protects the receiver from the external air stream.

1. Introduction

Among line-focusing technologies for Concentrated Solar Power (CSP), the parabolic trough is the current leader, established at commercial level since the 80s (SEGS plants in California, USA).

More recently, the Linear Fresnel Collector (LFC) has been proposed as a cost effective alternative to the parabolic trough technology (Morin et al., 2012; Sait et al., 2015). The cost reduction allowed by the LFCs is due to their constructive simplicity: there are no rotating joints or high-temperature moving components and the support structures are lighter than in case of parabolic collectors (Qiu et al., 2015). The possibility to use lighter structure is in fact a consequence of the low mirrors altitude and wind load (Lancereau et al., 2015).

A LFC system consists of a set of parallel-placed flat or slightly curved mirrors stripes, which focus the solar radiation onto a fixed linear receiver. To minimize the shading and blocking effect due to the adjacent mirrors, the Compact Linear Fresnel technology has been proposed (Mills and Morrison, 2000), which also allows reducing the

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land usage since the mirrors stripes can be installed very close to each other. This technology employs two receiver lines for each solar field; thus, the mirrors have two possible orientations that allow optimizing the solar field. From a thermal point of view, the LFC is competitive with respect to the more widespread parabolic trough technology. Montes et al. (2016) developed a 2D model based on a thermal resistance scheme to study the thermal behavior of a receiver mounted in a CPC cavity closed at the bottom by a glass plate concluding that the LFC performs better than the parabolic trough in terms of receiver thermal efficiency. Nevertheless, the overall efficiency of the LFCs is lower than the one achieved with the parabolic trough collectors due the poor optical performance of the Fresnel systems. Innovative LFC layouts have been proposed with the aim to overcome the gap in optical efficiency compared with the parabolic trough; as for example in (Canavarro et al., 2014). Two configurations can be identified for the receiver of the LFC: the single-tube receiver and the multi-tube receiver. The former includes an absorber tube mounted in a cavity consisting of a secondary concentrator, like a Compound Parabolic Concentrator (CPC). The cavity can be closed at the bottom with a glass plate, in order to reduce the radiative (greenhouse effect) and convective losses. As an alternative, the absorber tube can be encapsulated in a glass envelope, see (Grena and Tarquini, 2011; Qiu et al., 2015). Absorber tubes encapsulated in a glass cover are widely used in parabolic trough systems, as they allow evacuating the gap between the absorber and the glass tube. This should lead to a reduction of the convective losses and protect the selective coating of the absorber, since the stability in air of these coatings at high temperatures is still an open issue (Raccurt et al., 2015).

This paper concentrates on a receiver with a single tube configuration, equipped with an encapsulated absorber tube, aiming at studying the radiative and convective heat loss mechanisms that lower the receiver efficiency. According to the current literature, the single tube still represents a promising design for the Fresnel linear receiver, especially because it allows evacuating the absorber tube, which can be a key advantage in terms of heat losses reduction and coating stability. The paper considers both the evacuated and non-evacuated (i.e. simply encapsulated) cases, with thermal oil as the heat transfer fluid (HTF), and the two configurations are compared in terms of performance.

Several projects have been based on the single tube configuration, including the Fresdemo prototype (Bernhard et al., 2008), that was built at the Plataforma Solar de Almeria in Spain to demonstrate the maturity of the LFC technology.

Heimsath et al. (2014) numerically investigated the heat losses from a single-tube receiver that employs a CPC cavity with a flat glass cover (glass-plate receiver). The analysis was performed using both a CFD model coupled with a ray tracing code that provided the absorbed heat flux over the secondary concentrator and a faster model based on a thermal resistance scheme. In the CFD model, the absorber tube temperature was imposed and the computational domain didn't include the external air. The main conclusion of this work was that the impact of the heat absorbed by the secondary concentrator cannot be neglected to accurately evaluate the heat losses from a glass-plate receiver. Because of the different receiver design (glass-plate VS encapsulated), this result is not applicable to the cases analyzed in the present paper.

Qiu et al. (2015) investigated the optical and thermal performance of a single-tube receiver with a CPC cavity and an evacuated absorber tube coupling a Monte Carlo ray tracing code with a finite volume model. The results from this study indicated that using cylindrical mirrors instead of parabolic leads to achieve nearly the same performance, but it allows reducing the mirrors cost since the cylindrical shape is easier to be manufactured. In addition, this work concluded that the heat losses strongly depend on the temperature difference between the coolant and the ambient, while they are weakly influenced by the DNI (Direct Normal Irradiance) level (where the radiation is always assumed at normal incidence) since most of the heat is in any case transferred to the HTF, and namely molten salts. Thanks to the vacuum in the gap, they found that the thermal efficiency is always above 70%.

Recently, Montes et al. (2017) compared different single-tube receiver designs using numerical thermal resistance models; all the designs considered were equipped with a CPC secondary concentrator. This study concluded that the best thermal performance is obtained using an evacuated absorber tube, followed by the glass-plate receiver, where the absorber tube is not encapsulated, but the cavity is closed at the bottom with a flat glass, and finally by the nude receiver, where the absorber tube is not encapsulated and the cavity is exposed to the environment. However, the performance differences among these designs becomes quite negligible if the absorber temperatures is low enough. For this reason, they proposed a hybrid configuration, which employs a nude receiver in the first modules (low temperature), while it adopts an evacuated absorber tube for the remaining modules at higher temperature. With respect to the work of Montes et al. (2017), in this paper the simply encapsulated absorber tube is studied instead of the nude tube and the effect of the wind direction is investigated by means of an innovative modeling approach.

The multi-tube receiver consists of an array of parallel absorber tubes arranged in a trapezoidal cavity that can be closed at the bottom with a flat glass. This receiver design has the advantage of a larger absorber area with respect to the single-tube configuration; however, there is no clear winner in terms of receiver performance between these two designs on the base of the current literature.

A number of works have been carried out to study the heat losses from a multi-tube receiver equipped with a trapezoidal cavity. According to (Qiu et al., 2016; Sahoo et al., 2013), the radiation mechanism dominates the heat transfer from the cavity to the external ambient; thus, the coating emissivity, which has to be kept as low as possible, plays a key role in reducing the heat losses. Based on that, the role of the radiative, as opposed to convective, losses will be investigated in the present paper on the receiver configuration considered here, and a parametric study will also be performed to investigate the effect of the coating emissivity.

Moghimi et al. (2015) considered a trapezoidal cavity provided with an array of parallel absorber tubes to demonstrate how to use the CFD commercial software ANSYS Fluent, based on the finite volume method, to perform both the ray trace analysis (2D model) needed to compute the absorbed heat and the conjugate heat transfer analysis (3D model). The accuracy of the optical model, which exploits the discrete ordinates method, was proved comparing the results with the ones obtained using a Monte Carlo ray tracing code.

As stated before, the aim of this paper is to estimate accurately the heat losses that occur from the absorber tube to the external ambient. A common approach available in the literature to perform such an analysis is to study the thermal behavior of the receiver unit (absorber tube + cavity) performing a Computational Fluid Dynamic (CFD) analysis, see for example (Haberle et al., 2002; Moghimi et al., 2015; Qiu et al., 2015, 2016). In these analyses, the coolant is included in the computational domain and a fixed heat transfer coefficient is assumed to compute the convective heat losses towards the external ambient. Other studies use 1D lumped models to predict the receiver behavior; these models are based on thermal resistance schemes and they typically calculate the convective heat losses by means of heat transfer correlations, e.g. (Heimsath et al., 2014; Montes et al., 2017, 2016; Singh et al., 2010).

In this paper a novel CFD-based approach has been adopted, which aims at estimating the convective heat flux towards the external ambient in a more accurate way. To do this, the actual interaction between the external air flow and the real geometry of the receiver unit has been simulated by means of a steady-state CFD model, considering both natural convection and different wind conditions. The computed convective losses are then used to feed a 1D model that allows the evaluation of the global efficiency of the Fresnel line. This method has been applied to investigate a reference operation condition (fixed day/time) in a detailed way, while the influence of the DNI level and of the sun