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Research Paper

Feasibility study of a new concept of solar external receiver: Variable velocity receiver

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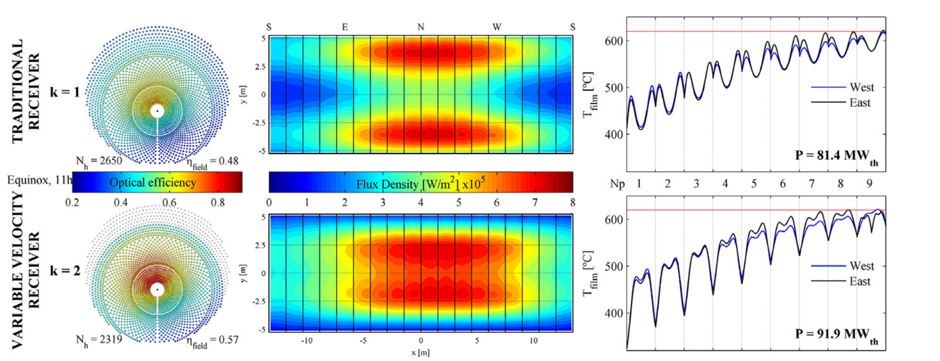
HIGHLIGHTS

- Variable velocity receiver allows doubling the mass flow rate in some panels.
- Reduction of the receiver wall temperature and increment of the field efficiency.
- Reduction of the solar field size in 12.5% keeping constant the power generation.
- Reduction of the total investment cost of the power plant in 5%.

GRAPHICAL ABSTRACT



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ABSTRACT

The deployment of new solar power tower plants mainly depends on becoming cost-competitive with traditional forms of electricity generation. The solar field represents around 40% of the solar power tower investment cost, thus the cost reduction of such subsystems is mandatory to achieve that goal. This reduction could be done by increasing the solar flux intercepted by the receiver, which would increase the peak flux. Therefore, new concepts of solar receivers are required to accommodate such high peak flux.

The proposed receiver, which withstands high peak flux, consists on a Traditional External Tubular Receiver (TETR) equipped with valves that allow the division of each panel of the receiver in two independent panels, increasing the velocity of the heat transfer fluid in specific zones of the receiver. This receiver configuration, named *Variable Velocity Receiver* (VVR), avoids tube overheating. Moreover, this novel receiver allows more concentrated aiming strategies, which increases the optical efficiency of the solar field and permits to reduce the number of heliostats in the field. Given a specific generation capacity, the size of the solar field required by a VVR is 12.5% smaller in comparison to a TETR.

Such efficiency improvement has a negligible effect in tube mechanical stresses; even though pressure drop and parasitic consumption of the power plant increase. This new receiver configuration also gains hours of operation, even in winter: in hours with low solar irradiance all the panels can be split in two, increasing the number of passes and the velocity of the heat transfer fluid and accomplishing the transition from laminar to turbulent regime. Therefore, this receiver is able to reduce the levelized cost of energy.

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1. Introduction

Solar power tower (SPT) systems use numerous sun-tracking mirrors to concentrate sunlight onto a receiver, situated at the top of a tower. Solar energy is collected in the receiver using a heat transfer fluid (HTF) which is then used to transfer the energy to a thermodynamic power cycle. Then, SPT consists of two main subsystems: one that collects solar energy and converts it into heat, and another that converts thermal energy into electricity. This study is devoted to the improvement of the first part of the SPT, which includes the solar field and the central receiver.

The main challenge for SPT is to increase the lifetime of the highly irradiated receiver, whilst ensuring a cost effective design. If the reflected solar radiation is concentrated on the receiver equator, high solar concentration ratio and high optical efficiencies of the field are achieved. It increases the generation capacity of the SPT or, alternatively, reduces the required size of the solar field for a given constant generation capacity, being crucial to economic feasibility of the SPT. However, high solar concentration produces overheating of the absorber material, accelerating the risk of failure by stress corrosion cracking. Hence, a multi-level aiming strategy is required to reduce the wall temperature, at the expense of reducing the efficiency of the SPT and, ultimately, its economic feasibility. Moreover, scattered aiming strategies require permanent control of the heliostats position, making SPT operation more complex.

Numerous researches focused their studies in optimizing the design of the receiver and the solar field to reduce the levelized cost of electricity. With respect to the solar field, Ruiz et al. [1] proposed a variable geometry central receiver facility, in which the solar field rotates around the tower axis, following the sun azimuth along the day and reducing the number of heliostats required. Related to the thermal storage, Hübner et al. [2] proposed a combined sensible molten salt thermal energy storage plus an alkali salt latent heat thermal energy storage, in order to increase the power generated by the SPT. Regarding the absorber materials, Neises et al. [3] tested a new receiver material that could withstand high solar flux and temperature, while Prasad et al. [4] designed single, double and triple layer absorber tandems to control the chemical oxidation and to improve the optical properties of the absorber material, the problem of this material is that cannot withstand high temperatures. Related to the HTF, Boerema et al. [5] compared the advantages of using different HTF and Rodríguez-Sánchez et al. [6] optimized the flow pattern of the external receivers which enlarges the useful lifetime of the receivers. On the other hand, several authors proposed new concepts of solar receivers, among them Garbrecht [7] studied a receiver geometry based on hexagonal pyramid-shaped elements, Rodríguez-Sánchez et al. [8] analysed an external receiver in which the tubes were replaced by bayonet tubes, Boerema et al. [9] investigated new designs using different tube diameters in each panel, Turner and Sansom [10] studied a low-cost modular receiver that consists on a volumetric cavity receiver formed by tubular structures, and Yang et al. [11] introduced a high temperature two-phase flat heat pipe receiver, with sodium as HTF, which homogenises the temperature in cavity systems. However, none of these designs can optimize the receiver design for the whole operational range in a SPT, which depends on sun position. Thus, SPT does not take advantage of the maximum energy available and tube overheating still takes place.

A new concept of external tubular receiver, named *Variable Velocity Receiver* (VVR), is introduced and analyzed from the point of view of mechanical and thermal limitations, as well as cost effectiveness. VVR can increase/reduce the velocity of the HTF in specific zones of the receiver thanks to a valve system; therefore it uses the advantages of a receiver with high number of panels without an elevated parasitic consumption. VVR can be adapted to the evolution of concentrated solar flux along the day, reducing the control load associated to the solar field. Moreover, the possibility of increasing HTF velocity in selected parts of the receiver, reduces tube overheating problems and allows higher concentration ratios in the receiver, reducing spillage losses [12]. Thus, the use of VVR reduces the number of heliostats required in the field and, ultimately, the levelized cost of electricity.

This paper describes the main characteristics of VVRs and presents their main differences with respect to Traditional External Tubular Receivers (TETRs). Firstly, the operation of the VVR has been described, as well as the optical and thermal model employed to characterize the instantaneous behaviour of the field and the receiver. Secondly, the configuration of the VVR has been optimized for a given generation capacity during the Spring Equinox. This optimization was based on the hourly thermal, mechanical and hydraulic behaviour. Finally, TETRs and VVRs of the same generation capacity have been compared.

2. Receiver configuration

In this study, the proposed receiver configuration is an external tubular receiver, based on Gemasolar power plant, located in Seville at 37.56° North latitude. The receiver is a 360° cylindrical external receiver of 10.5 m in height, *H*, and 8.5 m in diameter mounted on a 120 m high tower. The receiver is formed by 18 panels of 1.48 m width; in each panel there is one inlet header and one outlet header, located in opposite sides (top and bottom). The headers are connected by 60 vertical tubes of Alloy 800 H coated with black Pyromark. The external diameter of the tubes, d_o, is 0.0221 m and the thickness, *th*, 0.0012 m. In the rear part of the tubes a refractory wall reduces the thermal losses.

The HTF flowing by the receiver is solar salt (60% $NaNO_3$ - 40% KNO_3). This salt is heated from 290 °C to 565 °C. The inlet of the receiver is located at the two northern panels and the molten salt moves towards the southern panels in two different paths (East and West paths). The salt flows in parallel (i.e. same direction) through all the tubes of a panel, and in series from one panel to the following, as can be seen in Fig. 1a. The design thermal power absorbed by the salt in the receiver is 120 MW_{th}.

Using the same tube diameter, d_o, receivers with high number of panels, N_p, reduce the wall temperature of the tubes; however this kind of receivers has high pressure drop, which in turn increases the parasitic consumption of the SPT [13]. To take advantage of a receiver with high number of panels without its disadvantages, the concept of variable velocity receiver arises.

The VVR consists on a receiver with the same characteristics as the TETR. Additionally, each header is divided in two independent headers as the receiver proposed by Das et al. [14], called Alstom Receiver (AR). The new receiver has two inlets and two outlets headers per panel; each pair of headers connects half the number of tubes than the original panel of the TETR (30 tubes). Despite of the division the behaviour of AR is equivalent to the TETR since the new pair of panels works in parallel, keeping constant the number of passes of the receiver, see Fig. 1b. The novelty of the VVR with respect to the AR lies in the valve system installed between the headers of the same side (top or bottom). The valve system can keep the panel working as the AR, as shown Fig. 1c (pairs of panels working in parallel, keeping constant the number of passes of the receiver), or can divide the panels in two independent ones (working in series, and increasing the number of passes of the receiver). In order to improve the receiver behaviour, such divisions are only performed in those panels in which the wall temperature overpasses the safe operational limit, see Fig. 1d.