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Effect of the optical properties of the coating of a concentrated solar power central receiver on its thermal efficiency

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ABSTRACT

Solar receivers are one of the critical components of tower central receiver concentrated solar power plants (CSP), as this is where the light-heat conversion occurs. Better receiver designs provide higher plant efficiencies, better coupling with thermal energy storage and cost reductions. Current solar receivers are usually coated with a high sunlight absorptivity layer applied over the bare surface of the absorber receiver's tubes, in order to enhance their absorptivity and light-to-heat conversion. Here, we study the effect of the optical properties (viz. absorptivity and emissivity) of these coatings on the thermal performance of the receiver. The thermal performance of different coating candidates, solar selective and non-selective, were numerically simulated and compared against the current standard coating Pyromark 2500. Variation tendencies and the variation of the common accepted Figure of Merit (FOM) curve with temperature in different optical scenarios were also studied. Our results show that the thermal efficiency increases with the absorptivity of the coating (up to 4%). On the other hand, we observed that the emissivity has a very minor effect on the thermal performance of Molten Salt external receiver at its nominal working temperature, as the efficiency increases only by 0.6% when the emissivity of the coating decreases from 0.9 to 0.5 in a molten salts external receiver. Variation tendencies are also carefully analyzed, as well as the variation of the FOM curve with temperature in different optical scenarios for the design conditions of each receiver. At current molten salts working temperatures, improving the absorptivity of a non-selective coating leads to higher thermal efficiency than when using a selective coating. Nevertheless, for superheated steam cavity receivers, the effect of using a selective coating can be noticed at temperatures greater than 500 °C. These results can be used for selecting the optimum coating type for each type of receiver, incident flux and working temperature.

1. Introduction

Among the various concentrating solar thermal technologies, the central receiver solar tower system is the most suitable system for achieving high temperature processes. Technologies, methods and materials to utilize concentrated solar energy have been a broad and increasing field of research over the last few years. Recently, considerable effort has been made to reach higher operating temperatures and efficiencies in solar thermal systems, allowing concentrated solar power to become more affordable compared to other sources of electricity [1,2].

The basic design requirements demanded by industry for the central tower receiver include high reliability, cost-effectiveness and a long operational lifetime. The solar central receiver will operate in an environment different to fossil or nuclear steam generators. The receiver will be exposed to daily cycling from zero to peak power with a multitude of fast thermal and solar concentration variations due to cloud transients. Therefore, during operation, receiver materials undergo transient irradiation intensity that causes strong thermal stresses and may lead to fatigue and failure before the expected number of thermal cycles. Since the thermal losses of the system play a major role in the design of the receiver, the accurate prediction of the different thermal losses is vital to design the receiver thermal absorption elements properly.

The energy performance of the central receiver is given by its ability to convert the incident concentrated radiation into thermal power carried by the heat transfer fluid. This conversion is affected by four heat loss types: reflection, radiation, convection and conduction.

Abbreviations: CSP, concentrated solar power; MST, molten salt tower; FOM, figure of merit; ASTM, American Society for Testing Materials

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1.1. Two candidate receiver concepts

Two basic receiver concepts, a cavity and an external absorption surface, are analyzed. Both concepts use surrounding collector fields. The receiver design is highly dependent on the selected working fluid used to convey the absorbed thermal energy. Different HTFs have been tested so far to be used in central receiver systems, including: water/steam, nitrate salts and sodium.

Here, analysis of both external-type and cavity-type receivers has been conducted, with cavity receivers generally expected to have a lower radiative heat loss and higher convective heat loss than for external receivers (Fig. 1) [3].

When the receiver is located in a cavity, the heat losses are reduced, as the aperture size and atmospheric attenuation are decreased. Furthermore, the internal reflections inside the cavity decrease the optical and infrared radiative losses. A common way to build such a receiver is using metallic tubes.

The solar cavity receiver usually has only one aperture; thus, the sunlight projects onto the surfaces inside the receiver only from one side. The distribution of input solar flux itself is non-uniform in the aperture. Due to the two reasons mentioned above, the distribution of heat flux on the absorber panels appears to be highly non-uniform. About 50% of the energy is gained by the central panel and 25% by each of the side panels. The data calculated here are in good agreement with the results of Fang et al. [4].

The external receiver concept consists of different panels that approximate a vertical cylinder. In this system, the radiative heat losses will have a higher impact when the emissivity of the tube increases, as the tubes are exposed to air. The Solar Two project used an external tubular receiver with a molten nitrate salt working fluid that could accommodate fluxes of approximately 850 kW/m^2 (Fig. 2) [5].

Higher efficiency power cycles are being pursued to reduce the levelized cost of energy from concentrating solar power tower technologies. The unique challenges associated with high-temperature receivers include the development of geometric designs, materials, heat-transfer fluids and processes that maximize solar irradiance and absorptance, minimize heat loss and have a high reliability at high temperatures over thousands of thermal cycles. At elevated temperatures of 650–750 °C, re-radiation effects must be considered in order to select an open or enclosed receiver design. Increasing the solar absorptance, α, and/or decreasing the thermal emittance, ε, will also increase the thermal receiver efficiency.

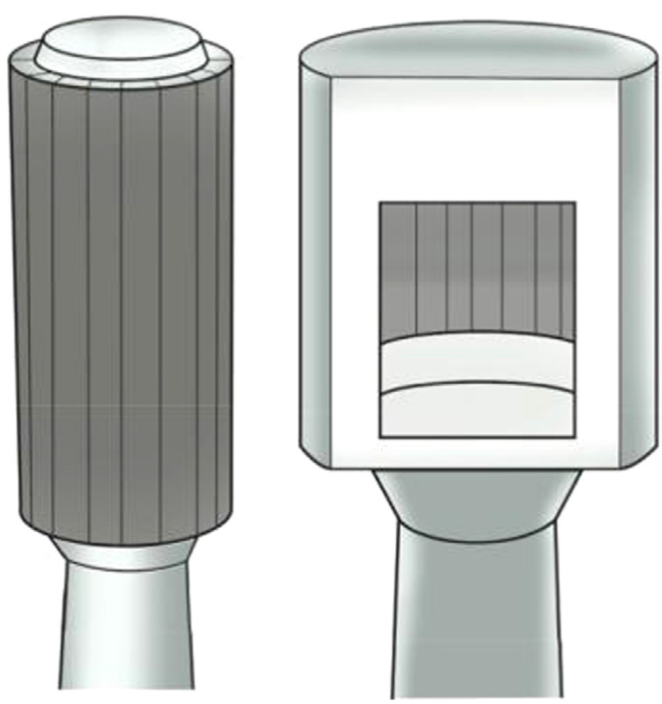

Fig. 1. Schematics of tubular (left) external and cavity receivers (right).

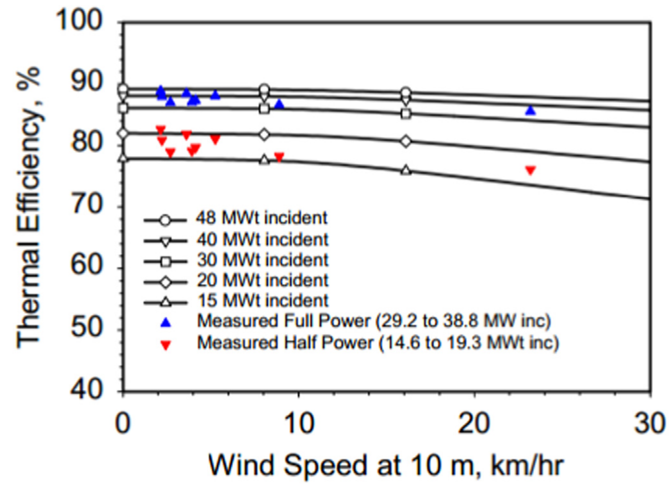

Fig. 2. Modeled and measured receiver efficiency as a function of wind speed for Solar Two [5].

1.2. Coating design

Usually, existing paint-based coatings with a very high absorptivity do not have a very long durability, as the deposition techniques employed (e.g. spraying, brushing etc.) do not interact significantly with the substrate, and therefore its adherence is limited. In a solar central receiver, the main factor affecting the coating delamination process is induced by thermal cycles to which the tandem coating-substrate is exposed. Hence, ongoing research lines focus on improving the adhesion, as the optical properties are proven to be maintained at tube surface temperatures higher than 650 °C.

An important advantage of a paint-based coating is the ease with which it can be re-applied. When a coating degrades, a re-application of a new coating is generally carried out by the plant operation and maintenance team in order to recover the initial performance power output. The process involves additional costs that generally are overcome with the new improvement in efficiency. Quantifying this cost based on the annual thermal energy absorbed was assumed to be affected by the collector efficiency, receiver efficiency (which includes the selective absorber efficiency) and parasitic losses.

The current coating used for tower receivers is a high-temperature black protective paint called Pyromark 2500. It has a high absorptance ratio in the solar spectrum. However, the emittance value is quite similar; therefore, radiative heat losses are also very high. It is considered as the reference value for many designs. Degradation rates and costs associated with Pyromark 2500, application, reapplication, downtime, and degradation can be assumed as presented data shown in [6]. The ranges of possible values from a pessimistic to an optimistic situation are also shown for each of the parameters presented (Table 1).

In order to evaluate other possible candidate materials under development, a range of various input parameters is considered for the analysis. The range of nominal values within a minimum and a maximum are estimated based on available data, considering in all the cases a plant life fixed at 25 years. Thermal emittance is almost unchanged, as only high solar absorptive coatings are studied in this case. Based on previously reported data [8], the