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ScienceDirect
Energy Procedia 49 (2014) 314 – 323
Energy Procedia

SolarPACES 2013

Alternative designs of a high efficiency, north-facing, solid particle receiver

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Abstract

Falling solid particle receivers can enable increased working-fluid temperatures for central receiver power plants, but will need to have high thermal efficiencies. This can increase power-cycle efficiencies and reduce thermal storage costs. A previous north-facing solid particle receiver (SPR) design was estimated to have a thermal efficiency of 72.3%. This design included a large aperture (17 m x 17 m), a slight downward facing nod (20°), a high-sloping ceiling to accommodate the beam angles from the closest heliostats, and particles released near the back wall of the receiver. Receiver design modifications have been introduced to achieve a thermal efficiency of >90% as stated in the SunShot initiative. Design changes including a reduced aperture size, bottom lip on aperture, increased nod angle, deeper cavity, reduced ceiling slope angles, and more specular walls resulted in higher thermal efficiency designs.

DELSOL was used to determine viable receiver dimensions, aperture sizes, and nod angles for a desired power output. The optimum receiver parameters were 10.63 m x 10.63 m aperture size, 50° nod angle, and a tower height of 194.7 m. The new aperture size had a higher concentration ratio and provided maximum incident power on the particles with minimum radiative loss. An aperture with a lip, nod angle of 50°, and extended back wall prevented buoyant hot air from leaving the receiver. A ceiling with higher reflectivity allowed more incident radiation to be reflected onto the particles rather than absorbed and thermally re-emitted.

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Selection and peer review by the scientific conference committee of SolarPACES 2013 under responsibility of PSE AG.
Final manuscript published as received without editorial corrections.

Keywords: concentrating solar power; solid particle receiver; cavity

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doi:10.1016/j.egypro.2014.03.034

1. Introduction

Falling solid particle receivers (SPR) can enable increased working-fluid temperatures for central receiver power plants. This can increase power-cycle efficiencies and reduce thermal energy storage costs. Solid particle receivers differ from traditional concentrating solar power (CSP) receivers in that they utilize small particles as the primary heat transfer fluid (HTF). These particles are typically ceramic based and are stable at high temperatures (>1000°C) [1]. However, there are current design challenges associated with this type of receiver. In order to accommodate a large heliostat field (100 MWe) the receiver aperture needs to be large (>10 m). The large dimensions of the receiver typically require particles to fall from a large height posing challenges for particle structural stability and heat loss. Complex air flow patterns develop within the receiver due to heating and particle movement which can cause large convective heat losses. Passive walls within the receiver lead to high radiation losses both due to reflection and thermal re-emission. Reducing heat loss is critical to achieving the highest possible thermal efficiency in the system. The SunShot initiative [2] sets the required receiver thermal efficiency goal of greater than 90% with particle temperatures greater than 700°C. Computational fluid dynamics (CFD) was used as a design tool to predict and optimize a north-facing SPR. The heating of the particles, stability of particle flow, and overall receiver heat losses are important metrics when finding an efficient design.

A previous north-facing SPR geometry [3] was used as the initial baseline design for this study. Previous work includes modeling of the north-facing and a face-down SPR. Khalsa et al. [3] utilized CFD to determine that the thermal efficiencies for both a north-facing and face-down SPR were 72.3% and 78.9%, respectively. The north-facing receiver in this work serves as the initial base-line case for the current study. This specific design was deemed a worst case scenario due to exclusion of an external air domain. Without an external air domain any hot air leaving the receiver cannot rise and re-enter through the aperture. Röger et al. [4] evaluated face-down SPR designs utilizing different particle recirculation schemes to maximize particle heating at different power loads. These particle recirculation schemes are critical to increasing particle residence time which increases thermal efficiency of the receiver. The general concept for these recirculation schemes are used in the current SPR work. However, these studies did not rigorously account for convective heat loss due to thermal buoyancy and particle entrainment. Further CFD analysis of these designs was performed by Gobereit et al. [5] and a thermal efficiency in excess of 92% could be achieved. Both the north-facing and face-down receivers could be utilized in CSP plants making it essential to understand the complex flow and thermal characteristics of each receiver design. This work focuses on the north-facing receiver.

A unique capability of simulating a distributed heat flux representative of a north-facing heliostat field was included in all current study simulations. The “solar patch” radiation boundary conditions methodology as described by Khalsa and Ho [6] was utilized. This radiation boundary condition allows modeling of the complex heliostat beam flux distribution within the receiver. Utilizing this radiation method allowed the falling particles to absorb radiation while also being coupled to the fluid flow solutions within the model. The result is a complex solution accounting for particle flow, radiative heat loss, and convective heat loss within the system.

2. Initial baseline SPR design and alternative designs

The initial baseline SPR design was considered to be the north-facing receiver from Khalsa et al. [3] due to the certainty that this receiver provides physically accurate results. The geometry is seen in Figure 1. The following heliostat field detailed in Table 1 (determined from the code DELSOL) drove the dimensions of this receiver. DELSOL optimized the field based on the annual performance of the plant while reducing the overall levelized cost of energy (LCOE). DELSOL calculations for radiative and convective loss are somewhat limited, but were informed by previous CFD analysis. While this receiver produced the required particle outlet temperature (>700°C), the thermal efficiency was found to be 72.3% and is below the required 90% for the system. Thus, designs to reduce the radiative and convective losses in the system needed to be considered. The initial baseline receiver geometry was modified based on another DELSOL analysis using SunShot parameters [2] and are reported in Table 1. Two assumed improvements are the heliostat mirror slope error and thermal-to-electric efficiency. The heliostat mirror slope error was modified from 1.835 mrad to 1 mrad based on possible future heliostat field optical improvements. The thermal-to-electric efficiency was changed from 28.5% to 50% based on perceived improvements by the

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