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Optical Design of a Heliostat Field for a High-Temperature Receiver–Reactor

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This study investigates the geometrical and optical characteristics of a high concentration ratio heliostat field, with an optional compound parabolic concentrator. The field is designed for application in a high-temperature redox thermochemical energy storage system. The target receiver–reactor cavity temperature is 1800 K, as required for the ferrite–manganese oxide reduction reaction. At this temperature, the thermal emission heat loss from the reactor is significant. A minimum concentration ratio C_{min} is determined as 594 suns that is required to achieve the stagnation temperature of T = 1800 K in a perfectly insulated and isothermal blackbody receiver. Far higher concentration ratios are required for a receiver to operate with a reasonable absorption efficiency.

The nominal solar power input and temperature of the reduction reactor are design parameters. The optical field performance is analyzed using an in-house developed Monte Carlo ray-tracing model written in Fortran. The model evaluates the optical characteristics of the heliostat field for specified sun positions, and incorporates the effects of selected sun-shape distributions, heliostat surface slope errors, and atmospheric attenuation. Aggregate annual performance simulations are based on sampling the optical performance at an array discrete sun positions, and integrating with weather data for a full year. A simple thermal model estimates the receiver emission losses for the determined aperture size. The optical field design is carried out by iteratively calculating the combined optical/thermal performance and then refining design parameters. Instantaneous and annual-averaged overall optical efficiencies of individual heliostats and entire heliostat field are predicted, accounting for cosine, shading, blocking, reflection, spillage and atmospheric attenuation losses, and also yield estimated aperture-plane flux distributions.

First, the case of a solar system without a CPC is investigated. The heliostat field boundary is trimmed by removing heliostats with an optical efficiency below a prescribed threshold $\eta_{\mathrm{opt,thr}}$. For each trimmed heliostat field created for a prescribed $\eta_{\mathrm{opt,thr}}$, the receiver aperture size is determined by maximizing the total efficiency η_{tot} calculated as the product of the field optical efficiency η_{opt} and the receiver thermal efficiency η_{th}. Next, the case of a solar system with a CPC is investigated. Heliostat field is trimmed by including heliostats with center points within an ellipse resulting from an intersection of the CPC acceptance cone with the field horizontal plane. The CPC entry aperture radius is then optimized to maximize the total efficiency η_{tot}, which now also accounts for the optical performance of the CPC. An example system evaluated numerically includes a field trimmed to match a CPC with an acceptance angle of 18° and an optimal aperture radius of 1.5 m. This system offers the radiative power input to the reactor of 2.3 $\mathrm{MW_{th}}$ at an average concentration ratio of 3148 suns, field optical efficiency of 70.5%, receiver thermal efficiency of 81.1%, CPC optical efficiency of 93.8%, and the total efficiency of 53.6%. The application of the CPC boosts the concentration ratio and the total efficiency, allowing for smaller heliostat fields to attain higher receiver temperatures at lower radiative power levels. Further optical and thermal performance gains are possible through design optimization.

High-temperature solar receivers suitable for use with redox thermochemical energy storage impose challenging design constraints on the geometric and optical characteristics of the heliostat field. Here, an integrated optical and thermal analysis demonstrates that a CPC can strongly increase the total thermal and optical efficiency of the collector, despite the reflection and absorption losses which occur in the CPC.