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Evaluating the Performance of Utility-Scale Falling Particle Receivers Subject to Wind

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1. Introduction

For next-generation concentrating solar power (CSP) energy generation, particles are being considered as viable heat-transfer media to achieve baseload CSP electricity cost targets [1]. Particles offer a number of advantages over competing technologies including: the absence of flux limitations on tubing in fluid systems, the experimentally demonstrated capability to reach high media temperatures (>700°C), and ability to directly store energy as sensible energy. A large source of uncertainty in the implementation of particle-based CSP plants is the performance of particle receivers subject to highly variable environmental conditions like wind. Experimental and numerical studies of falling particle receivers (FPRs) have demonstrated that the thermal efficiency can be affected by both the wind speed and direction [2].

Sophisticated system models have been developed and are frequently used to evaluate the levelized cost of electricity (LCOE) for 100 MW_e scale particle-based CSP plants. However, a critical piece of these models is the thermal performance of the particle receiver. Previous numerical studies at smaller scales have shown that advective losses are one of the largest loss mechanisms for FPRs [3], and those losses are a complex function of the receiver cavity geometry, the particle temperatures, the particle curtain release location, and other variables. Models necessary to capture the effects of these variables are typically too computationally expensive to be integrated directly with a system model. Instead, correlations of the receiver performance under different wind conditions derived from higher-fidelity models are needed to account for these effects.

This paper evaluates a FPR for a candidate 100 MW_e particle-based CSP plant to quantify the effect of sustained winds on the receiver's thermal performance. The FPR design being explored is part of a three-receiver power tower concept that enables smaller receiver cavities that are less susceptible to wind and reduce advective losses. Using computational fluid dynamics (CFD) simulations of the receiver cavity, the thermal efficiency is computed under a range of wind speeds and directions. The results of this study are used to develop correlations of the receiver's performance that can then be used to inform system models of a particle-based CSP plant.

2. Numerical Model

A Lagrangian–Eulerian CFD model is the framework for the FPR model using ANSYS Fluent. In this receiver model of a candidate 100 MW_e CSP plant (depicted in Figure 1a), Lagrangian particles with a diameter of 300 μm fall through the receiver cavity (Figure 1b) via gravity and are coupled to the air

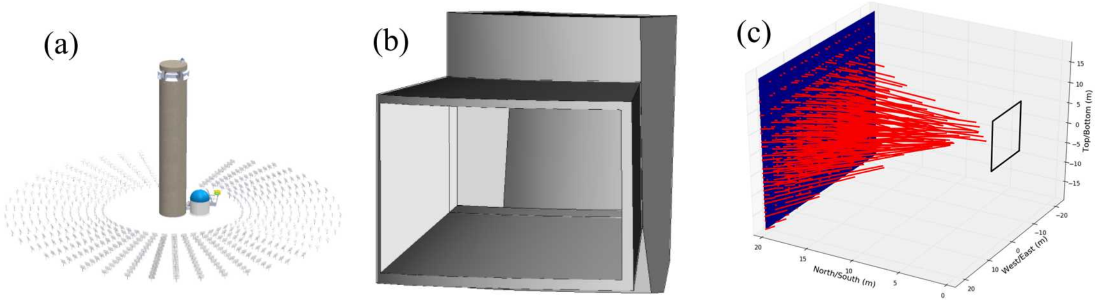

Figure 1. Depiction of the three-receiver power tower (a), solid model of the proposed FPR cavity (b), and a plot of the radiative flux from heliostat field

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continuum via drag, heat transfer, and turbulent interactions. Air is modeled both inside and outside the receiver cavity in a sufficiently large domain enabling the inclusion of wind. NREL's SolarPILOT, is used to generate a compatible heliostat field, and the integrated ray-tracing code is used to simulate the radiative flux through a plane a fixed distance from the aperture. This flux profile is used as a boundary condition for a non-grey discrete-ordinates radiative transport model of the FPR (Figure 1c).

3. Modeling Results

A parametric study is performed quantifying the receiver's performance while varying the wind speed (up to 15 m/s), wind direction, incident radiative power to the receiver (100 – 300 MW), and the particle mass flow rate (400 – 1040 kg/s). Only the central receiver is simulated (Figure 2a) to simplify the parametric study and the presence of additional receivers is assumed to be negligible. At nominal, quiescent conditions for an incident thermal power of 200 MW, the thermal efficiency of the receiver is 83.5% with 8.5% of the losses attributed to advective losses and 7.9% attributed to radiative losses in all wavelength bands. The performance of the receiver is reduced due to wind speed and direction up to a maximum of 8.2%-points at nominal conditions. Model results showed western to northwestern winds are the most detrimental to efficiency.

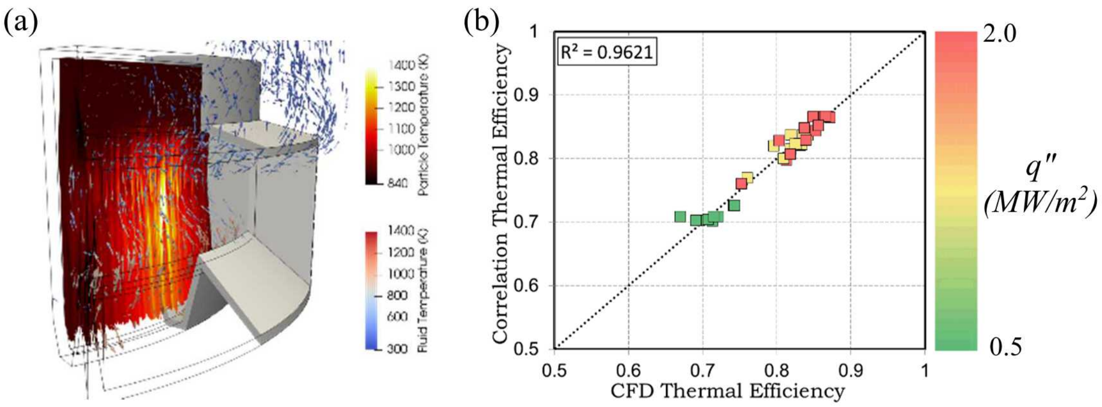

Figure 2. CFD simulation of the FPR depicting particle and air temperatures (a) and resulting correlation of the thermal efficiency developed from the correlations (b)

A correlation was derived from the parametric study using Minitab. The receiver efficiency was found to be a function of the incident power, particle mass flow rate, wind speed, and wind direction. The resulting correlation was found to have a coefficient of determination of 0.96. The correlation is plotted against the CFD results in Figure 2b and shown to be an excellent fit for the range of parameters explored.

4. Conclusions

A parametric CFD study was performed on a candidate 100 MWe utility-scale FPR to evaluate its thermal efficiency. The results of those simulations were used to derive correlations for the receiver efficiency as a function of the radiative power, mass flow rate, and wind conditions. These correlations can then be used in system models to more accurately predict the LCOE including the sensitivity of receiver efficiency to wind.

References

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