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Particle Receiver Models for Systems Analysis

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Abstract. Particle receivers are gaining importance in the field of Concentrating Solar Power (CSP) due to the high temperature that particles can achieve without degradation. Several researchers are studying the potential of this technology by means of system analyses, which need simple and light models of the system. This study presents two simple models for the particle receiver. The simplest model is a correlation obtained by fitting the results calculated with a more complex receiver model simulated in CFD. The other model is a 1D model, which is benchmarked against the same CFD results. Although both models achieve high coefficient of determination, R^2, when compared to CFD results, the 1D model seems to provide more accurate results (especially during sunsets and sunrises). Both models are integrated into a tecno-economic model developed in previous work. The LCOE obtained with the 1D model is between 7% and 10% greater than the one obtained with the correlation.

Keywords: Particle, Receiver, Model, System Analysis

1. Introduction

Particle receivers are gaining importance in the field of Concentrating Solar Power (CSP) due to the high temperature that particles can achieve without degradation. These receivers can be integrated with high efficiency sCO_2 cycles to achieve a Levelized Cost of Electricity (LCOE) potentially lower than current commercial systems. Several researchers are analyzing how low the LCOE can get with the objective of achieving 0.06 $/kWh.

Techno-economic models have been used to analyze the LCOE of particle-based CSP systems in previous studies [1–3]. These models are composed of simplified subsystem models, mainly the solar field, the receiver, the storage and the power block. These subsystem models must be computationally light so that the behavior of the whole plant (i.e., all the subsystem together) can be simulated along time periods of a year. Complex subsystem models would lead to divergence in the simulations or to too long computational times.

The objective of this paper is to select the best model for the receiver subsystem. The problem is that there is little knowledge in the simulation of particle receivers, especially if we talk about simple models that can be integrated into system-level models. Even complex CFD models have found several problems to be validated against experiments [4]. So simpler models will have limitations that must be understood.

This study presents two simple receiver models developed for systems analysis. The simplest model is a correlation obtained by fitting the results calculated with a more complex receiver model simulated in CFD. The other model is a 1D model, which is benchmarked against the same CFD results. The results show the difference between the models and the CFD results, and the impact of these differences in the LCOE calculated with the tecno-economic model presented in previous work [5].

2. Models

Two models are presented to estimate the thermal efficiency of the receiver in system models: a correlation and a 1D model. Both models make use of the results obtained with the CFD model from Mills et al. [6] for different aperture areas and different conditions of thermal power input, temperature, mass flow rate and wind. Although the 1D model was previously presented [5,7], the current model has been updated and benchmarked against several CFD simulations proving to provide very similar results.

2.1 Correlation

The dataset of CFD results from Brantley et al. [6] is used to obtain a correlation for the receiver efficiency as a function of the CFD model inputs: the aperture area, the particle mass flow rate, the radiative input power, the wind speed, and the wind direction. The functional form of this correlation is as follows:

$$\eta = A + Be^{-Q/A_p} + C\left(e^{-Q/A_p}\right)^2 + De^{-Q/A_p}V\phi + EV^2\phi \tag{1}$$

where A through E are fitted constants, Q is the radiative power entering the aperture (in $\mathrm{MW_{th}}$), A_p is the aperture area (in m^2), V is the wind speed (in m/s), and ϕ is the wind direction modifier with the form:

$$\phi = \frac{(180-|180-\theta|)^F e^{-(180-|180-\theta|)/G}}{H} \tag{2}$$

where F through H are fitted constants and θ is the wind direction (in degrees where 0° and 360° is N and 90° is E). The constants for the fit are summarized in Table 1.

Table 1. Coefficients for the correlation of efficiency.

Constant	**Value**	**Constant**	**Value**
A	0.8481	E	-1.4575×10^{-7}
B	0.2498	F	5.5
C	-1.0116	G	7.5
D	-7.9429×10^{-5}	H	5000

This fit was found using the GRG Nonlinear Solving method from Excel. Figure 1 shows the comparison between the results obtained with the correlation and the results obtained by the CFD model, with a coefficient of determination, R^2, of 0.91.

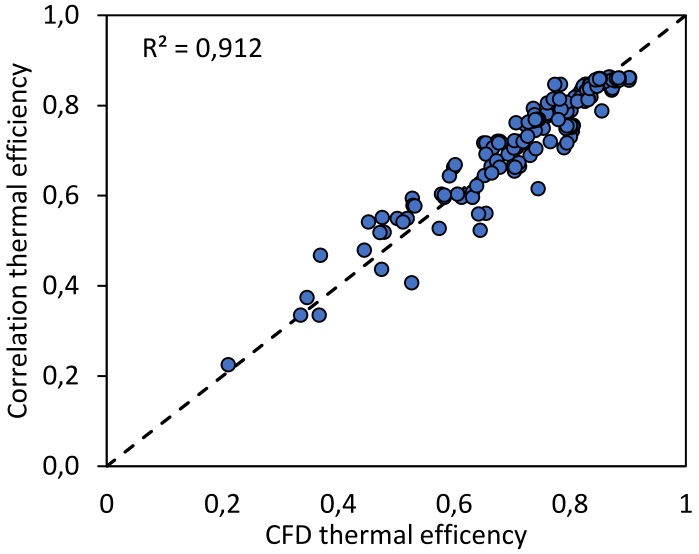

Figure 1. Correlation of the thermal efficiency compared with the CFD model.

2.2 1D Receiver Model

The 1D receiver model is composed of a particle curtain, a back wall and air as shown in Figure 2. The solar radiation enters through the aperture into the cavity. Aperture and particle curtain areas are the same, which is a simplification from the real design in which the aperture area is approximately 80% of the particle curtain. The curtain height is divided into 20 cells and the conservation equations are applied to each cell. The advection losses are calculated as

$$q''_{adv} = \boldsymbol{\psi_{wind} htc_{adv}}(T_p - T_{amb}) \tag{3}$$

and the radiation losses as

$$j_{c,front} = \boldsymbol{F_{view}}(\varepsilon_c \sigma T_p^4 + \rho_c g_{c,front} + \tau_c g_{c,back}) \tag{4}$$

where the parameters highlighted ($\psi_{wind}, htc_{adv}, F_{view}$) characterizes the receiver losses of a specific receiver design and they are considered constant along the curtain. The advection heat transfer coefficient htc_{adv} determines the advection losses under no wind conditions such as a convection heat transfer coefficient. The wind factor ψ_{wind} is defined as the ratio between the advection losses with wind and the advection losses without wind, i.e., it is used to account for the additional thermal losses produced by the wind. So, the wind factor ψ_{wind} will be 1 when there is no wind and greater than 1 when there is wind. The view factor $\boldsymbol{F_{view}}$ is a factor less than 1 that accounts for the radiation losses avoided by the aperture. More information about the model can be found in [5,8,9].

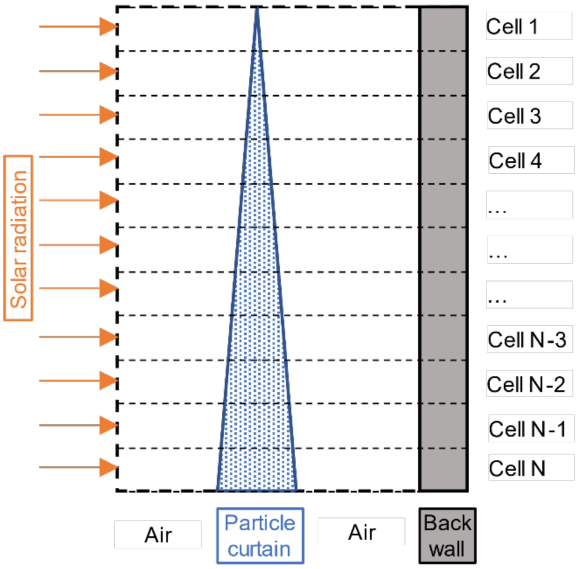

Figure 2. Diagram of the 1-D receiver model.

The advection heat transfer coefficient htc_{adv} is calculated by means of the Nusselt correlation:

$$Nu = J + K \cdot Re^{L} \tag{5}$$

where *J* through *L* are fitted constants and *Re* is the Reynolds calculated with the curtain height as the characteristic length.

The wind factor ψ_{wind} is represented as a function of particle height $\sqrt{A_p}$, wind speed V and wind direction θ as follows, where *M* through *N* are fitted constants.

$$\psi = 1 + (M - N \cdot \sqrt{A_p}) \cdot V \cdot \phi \tag{6}$$

$$\phi = e^{-\left(\frac{|\theta - P| - Q}{R}\right)^2} \tag{7}$$

The efficiency obtained with the 1D model can be approximated to the efficiency obtained with CFD from Brantley et al. [6] by fitting the values of advection heat transfer coefficient htc_{adv}, wind factor ψ_{wind} and view factor F_{view} with the GRG Nonlinear Solving method from Excel. The first step is to adjust advection and radiation losses by means of fitting the values of htc_{adv} and F_{view} under no wind conditions. Then, the wind factor ψ_{wind} can be fitted. The constants for the fit are summarized in Table 2.

Table 2. Coefficients for the 1D model [9].

Constant	**Value**	**Constant**	**Value**
J	-12331	P	178.7
K	1.949	Q	134.3
L	0.7002	R	27.49
M	0.2370	F_{view}	0.9
N	0.0089		

Figure 3 shows the comparison between the receiver efficiencies obtained with the CFD simulations and the 1D model. The comparison shows a $R^2 = 0.95$, which proves the greater reliability of the 1D model in comparison to the correlation. Note that although the 1D model was presented in previous studies [8], the current model has been updated and benchmarked against the new CFD results from Brantley et al. [6].

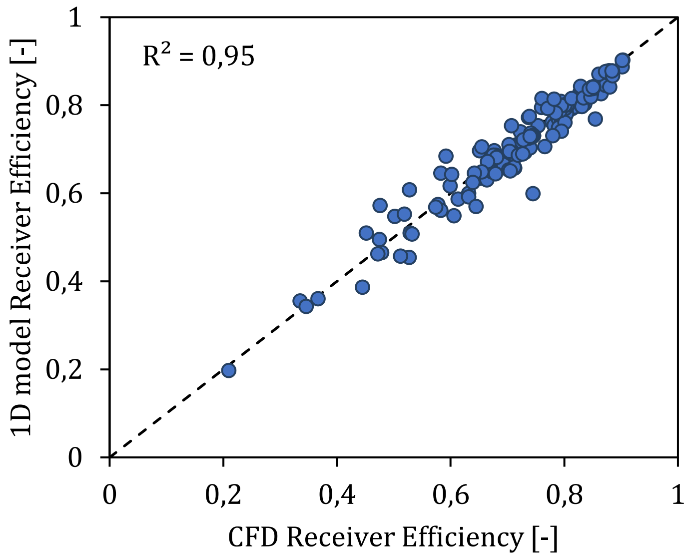

Figure 3. Thermal efficiency obtained with 1D model compared with the CFD model [9].

3. Results

The first part of the results shown in this study analyses the differences between the receiver efficiencies calculated with the correlation, the 1D model and CFD. The second part shows the LCOE obtained with the correlation and the 1D receiver models in the particle system model with three particle receivers from González-Portillo et al. [5].

3.1 Receiver Efficiency

Figure 4 compares the receiver efficiencies obtained with CFD, the correlations and the 1D model as a function of thermal input heat flux for different cases. Case A represents the cases simulated with CFD with inlet temperature set to 615 ºC and mass flow rate to 885.5 kg/s. In these cases (although not shown in the figure), the outlet temperature changes from case to case. Both correlation and 1D model present very similar results. The main differences are found at low and high heat fluxes.

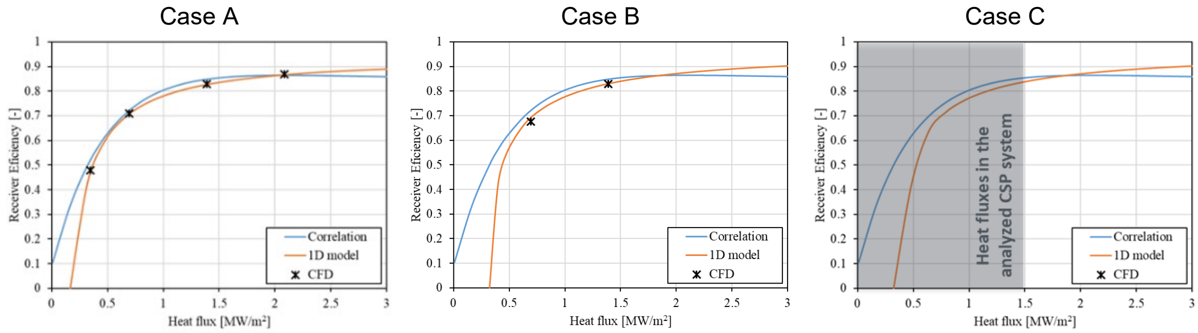

Figure 4. Receiver efficiency as a function of thermal input heat flux. Aperture area = 144 m^2 and no wind conditions. Case A: inlet temperature = 615 ºC and mass flow rate = 885.5 kg/s. Case B: inlet temperature = 615 ºC and outlet temperature = 745 ºC. Case C: inlet temperature = 578 ºC and outlet temperature = 800 ºC.

Case B represents the case where a specific outlet temperature is set, so the mass flow rate must be adapted to it. The results obtained from the correlation are the same than in case A since temperatures and mass flow rate are not variables of the correlation. The 1D model contains these variables and seems to better follow the CFD results. We can appreciate bigger differences in this case, especially at low heat fluxes.

Case C also fixes inlet and outlet temperature, but in this case to the values used in the techno-economic model from González-Portillo et al. [5]: 578 ºC and 800 ºC, respectively. In this case, there are bigger differences between correlation and 1D model in the range of values analyzed by the CSP system model. These differences are below 4% when the heat flux is greater than 0.7 MW/m^2, but increase significantly at smaller heat fluxes. This means that correlation and 1D model will have similar results when the receiver work at nominal conditions, but during sunsets and sunrises, the correlation will overestimate the efficiency.

3.2 Levelized Cost of Electricity

Both receiver models, correlation and 1-D model, are introduced in the technoeconomic model from González-Portillo et al. [5] to calculate the LCOE of a 100 MW$_e$ system with one, two and three receivers. The correlation is used to optimize the system configuration (solar field area, aperture area, tower height) due to its much smaller required computational time. Then, the 1D receiver model is employed to compare the results.

The LCOEs obtained are shown in Figure 5. The configuration with two receivers achieves the lowest LCOE, very close to the three-receiver configuration. These two configurations achieve an LCOE ~ 0.06 $/kWh if the correlation is used to model the receiver. However, this value increases up to 0.064 $/kWh when the 1D receiver model is employed to obtain more accurate results. This 7% difference between the LCOE obtained with the two models is due to the lower receiver efficiencies estimated by the 1D receiver model, especially when the power hitting the receiver is low (such as during sunsets and sunrises).

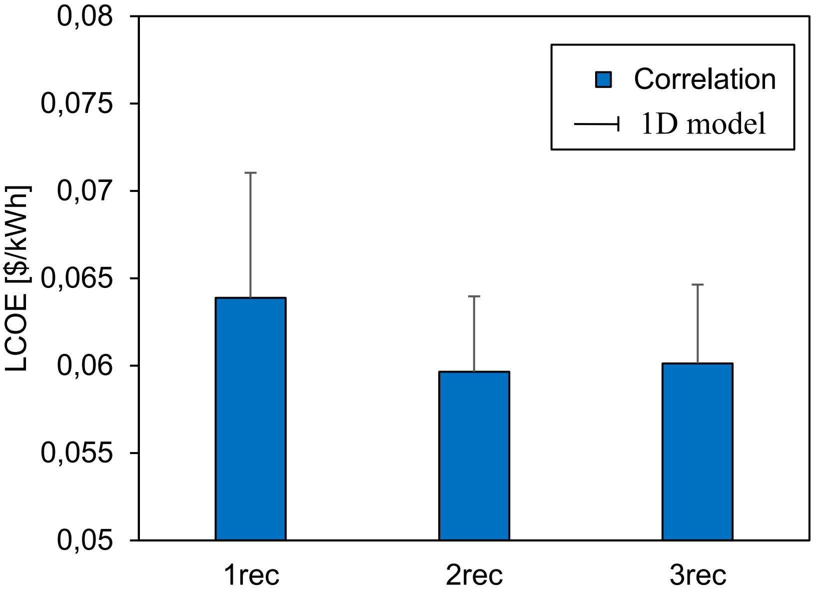

Figure 5. LCOE comparison for different number of receivers in a 100MWe CSP plant.

The difference between the results obtained for the case with one receiver is greater: 10%.

The higher LCOE achieved with one receiver is mainly due to a greater total capital cost. The land and the tower needed for the same solar field are bigger in the case of one receiver, which explains the greater the cost of the configuration.

4. Conclusions

Two receiver models were presented for its use in the techno-economic analysis of particle-based systems. The simplest model is a correlation obtained by fitting the results calculated with a more complex receiver model simulated in CFD. The other model is a 1D model, which is benchmarked against the same CFD results. Although both models achieved high coefficient of determination, R^2, when compared to CFD results, the 1D model seems to provide more accurate results (especially during sunsets and sunrises). Moreover, another advantage of the 1D receiver model is that it can be used, not only to analyze the receiver efficiency, but also other variables such as for example the back wall temperature.

The receiver models were integrated into a into a tecno-economic model developed in previous work to study the LCOE of a 100 MW_e system. The correlation was used to optimize the CSP system due to its faster computational time. Then, the LCOE is also calculated with the 1D model. The LCOE obtained with the 1D model is between 7% and 10% greater than the one obtained with the correlation. The authors show more confidence in the results obtained with the 1D model due its greater coefficient of determination, R^2. This means that the lowest LCOE achieved by the CSP system was 0.064 $/kWh.

Author contributions

Luis F. González-Portillo: Conceptualization, Methodology, Software, Writing-Original Draft, Visualization. **Victor Soria-Alcaide**: Software. **Rubén Abbas**: Investigation, Writing-Review, Editing. **Kevin Albrecht**: Software, Supervision. **Clifford K. Ho:** Supervision**. Brantley Mills**: Supervision, Funding acquisition.

Competing interests

The authors declare no competing interests.

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