Assessment of a Falling Solid Particle Receiver with Numerical Simulation

Birgit Gobereit[1], **Lars Amsbeck**[2], **Reiner Buck**[2], **Robert Pitz-Paal**[3], **Hans Müller-Steinhagen**[4]

[1]German Aerospace Center (DLR), Institute of Solar Research, Point Focusing Systems,

70659 Stuttgart, Germany, Phone: +49-0711-6862-519, E-Mail: birgit.gobereit@dlr.de

[2]German Aerospace Center (DLR), Institute of Solar Research, Stuttgart, Germany

[3]German Aerospace Center (DLR), Institute of Solar Research, Cologne, Germany

[4]Technical University Dresden, Germany

Abstract

With the face down cavity and a curtain of falling ceramic particles high receiver efficiency at high outlet temperature can be achieved, leading to a high overall efficiency of a solar power plant. The falling particle receiver is a promising concept for large scale power generation with low Levelized Electricity Costs (LECs).

An advanced computational fluid dynamic (CFD) model was developed, which allows detailed analysis of the face down particle receiver and its interaction with the surrounding air. The effect of wind on the particle curtain can be assessed.

The CFD model includes the interaction between the particles and the air. The particle curtain, the solar radiation, the thermal radiation transfer and the heat transfer due to convection are spatially resolved in three dimensions. The coupled equations for thermal radiation and convective heat transfer are solved by iteration. First results are compared with previous calculations with a simple Matlab model and the differences due to the improvements in the calculations are discussed.

The receiver efficiency was determined to 83 % at 100 % load, resp. 394 MW solar input power. With the recirculation strategy, the reflection losses can be reduced. With three recirculations a receiver efficiency in excess of 92 % can be obtained.

Wind effects have been studied for the cylindrical face down receiver for the 100 % load case with only one recirculation. For 15 m/s horizontal wind speed the receiver efficiency reduces from 89 % to 84 %.

Keywords: solid particle receiver, electricity generation, high temperature, direct absorption, computational fluid dynamics (CFD), wind effects

1. Introduction

For solar tower power plants with particle receiver high efficiencies, low construction costs and therefore low Levelized Electricity Costs (LECs) are expected. To illustrate the potential for the efficiency increase the theoretical maximum power plant efficiency is plotted in Figure 1. If one considers only the thermal radiation losses from the receiver, this leads to an estimate for the upper limit of the receiver efficiency. The theoretical maximum for the power block is given by the Carnot efficiency. In comparison to present state of the art, increasing concentration and receiver outlet temperature, higher power block and overall efficiencies can be achieved.

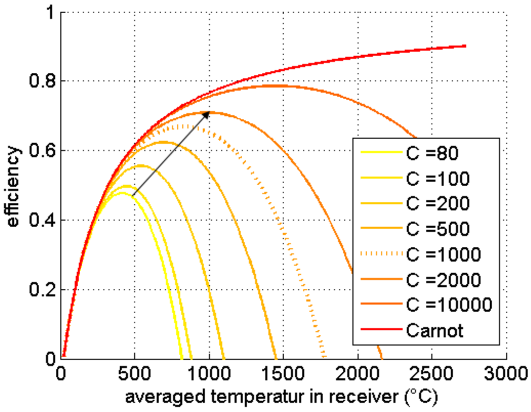

Fig. 1: Theoretical maximum of power plant efficiency

To reduce the specific investment costs for the power block and to increase the power block efficiency, the use of relatively large steam turbines is advisable. Power plants with a single tower and a high-power receiver as well as multi-tower arrays with several small receivers are possible to provide the required power. In combination with a thermal storage, on demand power generation can be achieved.

A schematic representation of a power tower with a face down cavity receiver is shown in Figure 2. Receiver losses can be minimized with such a receiver geometry. Due to the cavity effect, reflection and thermal radiation losses are reduced. The horizontal, downwards facing aperture leads to low convection losses without requirement for a window or other additional efforts like an air curtain.

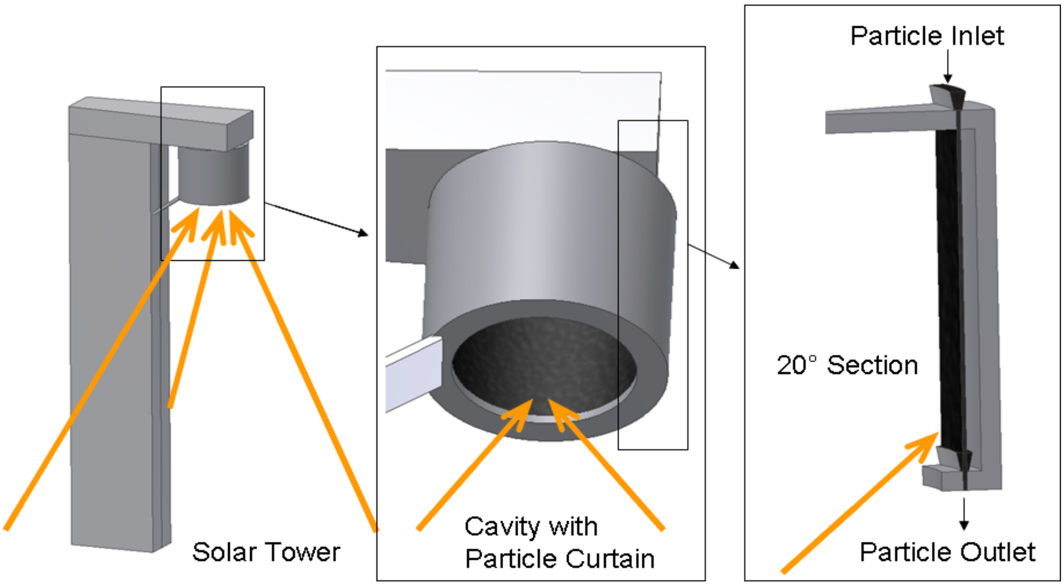

Fig. 2: Solar power tower with face down cavity (left); face down cavity with particle curtain, view from below (middle); segment of cavity and particle curtain (right)

The considered ceramic particles are cheap and available in adequate quantity. They can be used as absorber, heat transfer and storage medium. The direct storage of the heat transfer medium avoids additional costs for a heat exchanger and the associated exergy losses.

With the face down cavity and a curtain of falling ceramic particles high receiver efficiency at high outlet temperature can be achieved, and therefore high overall efficiency for a solar power plant.

2. Advanced Receiver Modeling

2.1. Modeling

Preliminary work involving different modeling approaches indicated high receiver efficiencies. A simple screening Matlab model and a computational fluid dynamics model have been presented, so far [1-3].

An advanced model was developed to assess all significant physical effects in the face down particle receiver in detail. The model takes into account solar radiation, particle movement, radiative and convective heat transfer, fluid dynamics in the air as well as wind effects. Major improvements are the consideration of the influence of the surrounding air and the treatment of the particle curtain, which is spatially resolved in three dimensions.

The air in the cavity and in the surrounding is modeled with computational fluid dynamics (CFD). For the turbulence the SST-Model is used. Automatic wall functions are implemented to model the near wall region adequate to the grid solution. With the Euler-Lagrange method the interaction of the air and the particles is computed. The interaction between particles and air is governed with the Schiller-Naumann equation. The spatial volume fraction distribution is used for the determination of the solar source terms. With a Monte

Carlo ray tracing algorithm volumetric heat sources for the discrete volumes and flux density distribution for the cavity walls are provided. The heat sources and the flux distribution are used as input for the CFD calculations. In addition to the movement of air and particles, heat transfer is determined with the Ranz-Marshall equation. The thermal radiation exchange is calculated with the discrete ordinate model. This modeling approach is a compromise between accuracy and computational effort. To properly calculate the convective air flow in the aperture, a part of the surrounding air outside the cavity is included in the model.

2.2. Numerical assessment

A grid study has been performed with four hexahedral meshes with 67 000, 178 000, 1 500 000 and 6 300 000 nodes in the cavity. The radiation losses were not sensitive to the grid refinement in the considered range. The mayor changes with the refinement can be observed for the convective losses. They converge to a solution, which can be extrapolated. With a grid size of about 1.5 million hexahedral elements in the cavity the solution differs from that extrapolated value by less than 0.1 %-point. Hence, this intermediate grid spacing has been proven as sufficiently fine.

For large scale receivers, it is not possible to solve the equations for all particles. For this reason only representative particles are considered. For a 350 $\mathrm{MW_{th}}$ receiver and a typical mass flow of 500 kg/s, there are about one billion real particles. A particle rate of 100 000 per second for the intermediate grid is adequate to determine global quantities like the relative losses. To analyse local quantities, a ten times higher particle rate is recommended.

For the radiation calculation with the discrete ordinate model, two numerical parameters were under examination to determine the optimal discretization. A grids coarsening factor of 64 with respect to the grid for the fluid dynamic calculations and a number of 8 rays have been found as a good compromise between computational effort and accuracy of the solution.

The Monte Carlo ray tracing was executed with 20 Million rays for the 1.5 Million element grid and to determine global quantities. Again, for detailed assessment of local quantities, more rays are recommended.

3. Receiver efficiencies for different operational strategies

3.1. Model Parameters

A receiver for a thermal power output of about 350 $\mathrm{MW_{th}}$ at 800°C was chosen to be comparable with the simple Matlab model from Röger et al. [3]. Furthermore, the same site, the same heliostat field, the same receiver geometry and the same particle properties have been used. The key parameters for the model are summarized in Table 1.

Parameters	Header
Design power	350 $\mathrm{MW_{th}}$
Temperature level	300°C → 800°C
Site	Dagget, CA, USA, 34.5 deg N
Aperture diameter	22.1 m
Receiver height	21.5 m
Particles	sintered bauxite, 0.7 mm diameter

Table 1: Key parameters for the modeling of the reference cases used in [3]

To increase receiver efficiency, the recirculation strategy is used for the calculations. Recirculation means that the particles drop more than once through the receiver. Hence, they reach the desired outlet temperature of 800°C without reduction of the mass flow, even at part load. With the increase of the mass flow, the reflection losses can be minimized.

3.2. Comparison of results from CFD and Matlab Model

To be comparable with the Matlab model (MM), the same mass flows were chosen for the first calculations with the CFD model. Thus, the outlet temperature is not exactly 800°C. In case of no recirculation, the average outlet temperature was 824 K, in the case with two drops 805 K, and in the case with four drops 797 K.

With an adjustment of the particle mass flow and an improvement of the recirculation strategy, the desired outlet temperature of 800°C can be exactly reached with only small changes in the efficiency.

Figure 3 shows the results for the relative losses from both models for the case of no recirculation (left side) and with recirculation (right side).

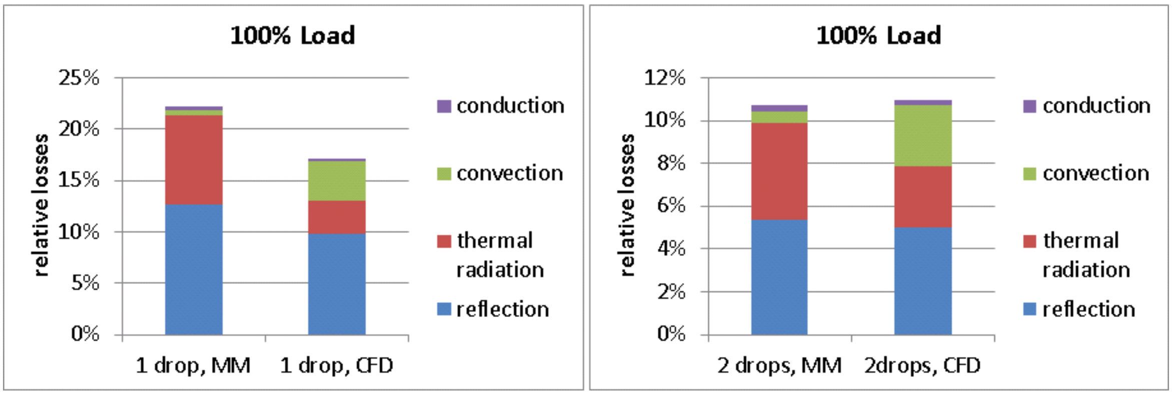

Fig. 3: Relative losses, 100 % load case, comparison of results from Matlab model (MM) and CFD calculations; left side: 1 drop, resp. no recirculation; right side: 2 drops, resp. one recirculaition

As one can see, the reflection losses from the CFD model are slightly lower than the Matlab results. It can be found that the reflection losses from the different models are in rather good agreement at high mass flow rates, but differ by more than 10 %-points at low mass flow rates (see Fig. 4).

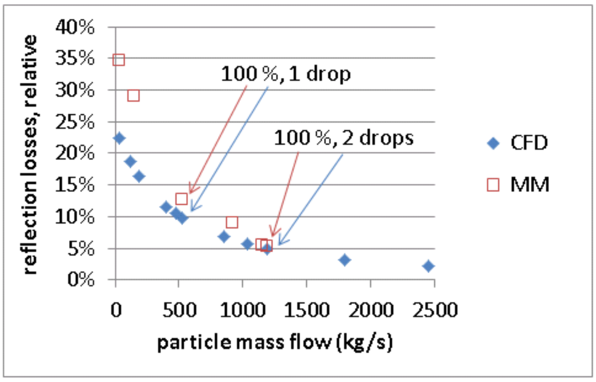

Fig. 4: Variation of the reflection with changes in particle mass flow.

The particle velocity in the Matlab model is calculated with a correlation, which assumes the air velocity to be 70 % of the particle velocity [1]. With the CFD model the air entrainment is locally resolved and therefore the calculated particle velocities and the volume fraction is more reliable. Also, the consideration of multi reflection in the cavity in the new model leads to a decrease of the reflection losses.

Regarding the thermal losses due to convection and thermal radiation, one can see, that the thermal radiation losses in the Matlab model are much higher than in the CFD model (fig 3). On the other hand the convection losses are determined to be significantly lower. This is due to the fact that the convective losses for the Matlab model are not taken into account during the calculation, but estimated afterwards. In the CFD model the thermal radiation and convection are calculated coupled, which is closer to the physical reality. Due to the coupling, the particle temperature and the radiation losses are decreased by the convective cooling. The thermal radiation losses calculated with the Matlab model constitute more than 90 % of total thermal radiation and convective losses, whereas according to the CFD model they are responsible for slightly less than 50 %.

In total, the overall efficiency for the case with no recirculation is 5.1 % higher according to the CFD model calculations and 0.2 %-points lower in the case with four drops, in comparison to the Matlab model.

3.2. Results

With the CFD model, the receiver efficiency was calculated to be 83 % for case without recirculation. With an improved operational strategy, the calculations indicate that the efficiency increases to 89 % with one recirculation and is in excess of 92 % with three recirculations.

The efficiency increase with increasing mass flow is mainly due to reduced solar reflection losses from almost 10 % down to 2.2 % (see Fig. 5). Convective losses add up to 3.8 % in the case without recirculation and decrease slightly with increasing mass flow. This is due to the lower heat losses at the wall associated with the lower wall temperatures. The temperatures are lower, because the curtain transmissivity decreases with increasing mass flow. Thermal radiation losses were calculated to be 3.2 % for the one drop case. With increasing mass flow it decreases by 0.6 %-points. This is also attributed to the lower wall temperature. Conduction losses contribute only a small amount between 0.2 % and 0.3 %.

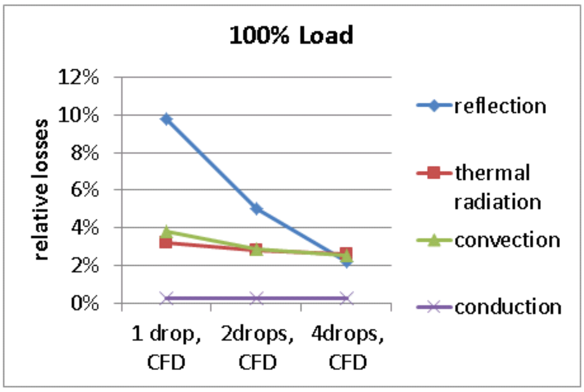

Fig. 5: Relative losses at different recirculation strategies.

4. Wind Effects

4.1. Model Parameters

For the assessment of the wind influence the same model parameters (Tab. 1) were chosen. In addition, an inlet boundary condition was implemented to simulate side wind. The wind was assumed to be horizontal and wind speeds up to 15 m/s were taken in to account. The case with 2 drops, respectively one recirculation was simulated. Again, as the input power and the mass flow have been kept constant, the outlet temperature varied between 760°C and 780°C.

4.2. Results

In Figure 6 the flow field in the middle plane for the simulated cases is shown, the reference case with no wind and with side wind at three different wind speeds. Particle tracks are not plotted, but one can identify the high velocities at the edges of the cavity, where the air is accelerated by the falling particles.

The side wind enters the domain from the left side and the cavity at the right edge, forms a vortex and leaves the cavity near the middle of the aperture. At low wind speed, the flow field is not much affected. With increasing wind speed from 5 m/s to 10 m/s the vortex height increases from about one third to half of the cavity height. As the wind speed was increased to 15 m/s the vortex height did not increase significantly, but the width.

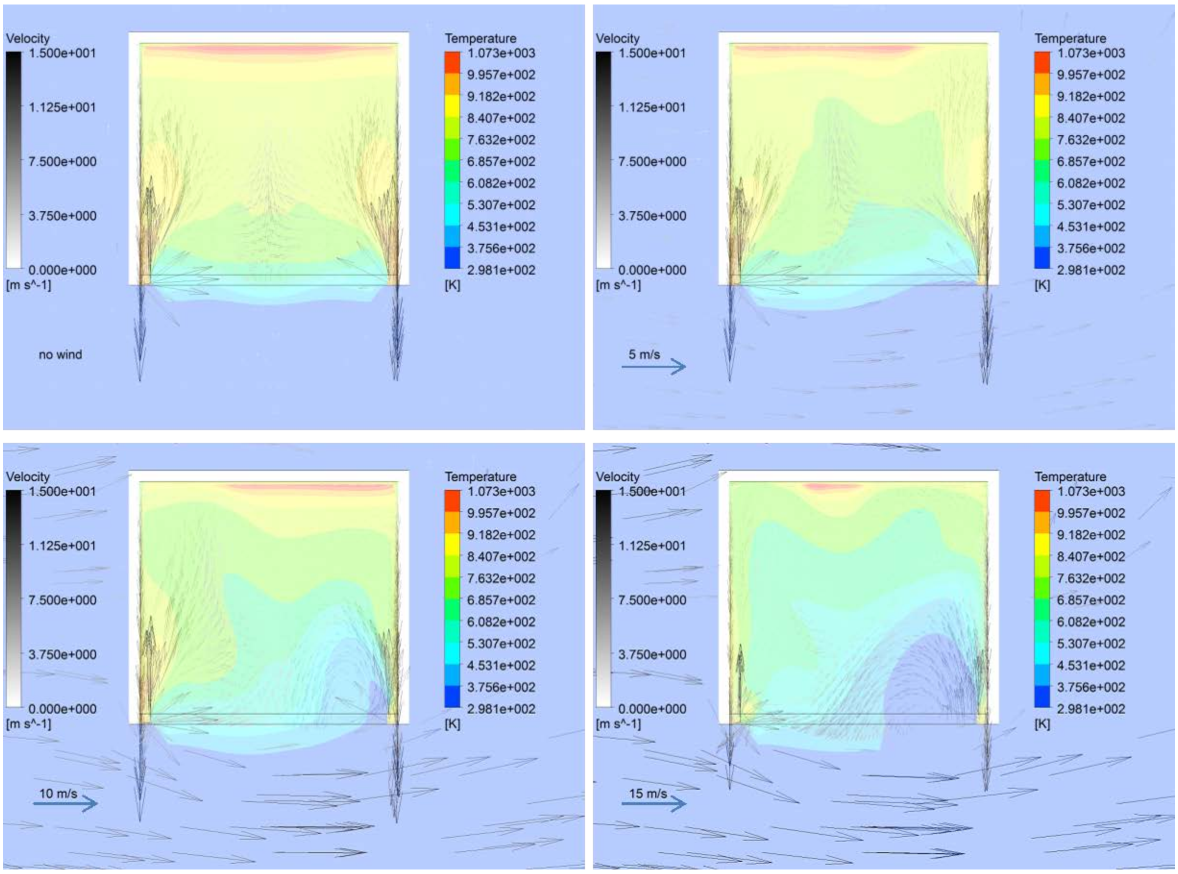

Fig. 6: Flow field in middle plane for different cases: no wind and with horizontal side wind, wind speeds 5 m/s, 10 m/s and 15 m/s.

This vortex leads to a decrease of efficiency, due to an increase in the convection losses. The receiver efficiency reaches up to 89 % without wind and is reduced to 84 % in the case of 15 m/s side wind (Fig. 7, left). The graph on the right side of Fig. 7 shows the brake down of the different losses. Reflection, conduction and thermal radiation losses are not significantly affected by the wind. However, the convection losses are calculated as 3.0 % without wind, and more than doubled in the case of 15 m/s wind speed. In this case the step-up was 5.4 %-points.

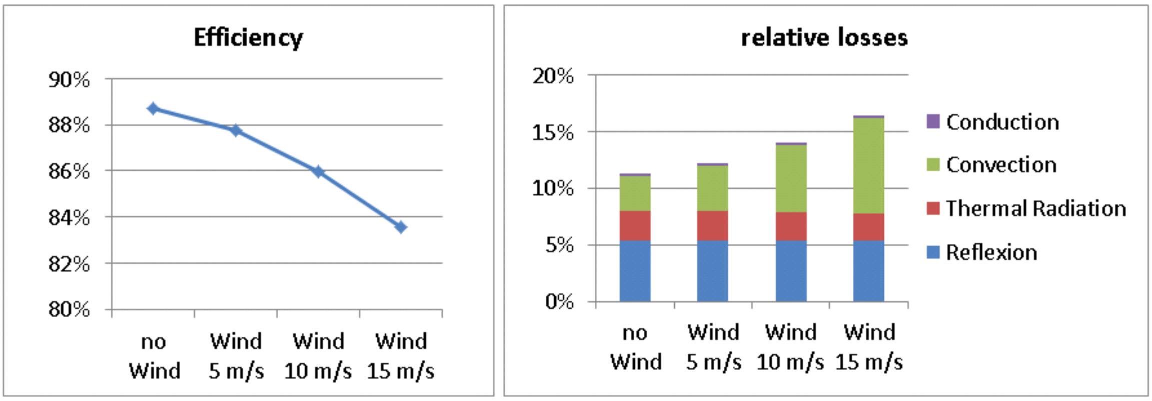

Fig. 7: Wind effect on receiver efficiency (left) and on the relative losses (right)

To minimize the convection losses in case all cases, a wind shield is recommend. This shielding has to be designed properly to avoid that the appearing vortex enters the cavity, but without blocking the incoming solar radiation. A wind shield might be a cheap possibility to yield high receiver efficiency with the open receiver even under windy conditions.

5. Conclusion and Outlook

A particle receiver is a promising concept for increasing system efficiencies of solar tower power plants. With the developed advanced model, the receiver efficiency can be determined and detailed information about the losses is available. The interaction with the surrounding is included more adequately and, therefore, the influence of wind can also be assessed.

First results confirm the results of previous calculations of receiver efficiencies, especially the fact that recirculation can increase receiver efficiency due to the decrease of reflection losses. With three recirculations a receiver efficiency in excess of 92 % is determined.

For the receiver design, the gain in receiver efficiency due to recirculation has to be compared to the additional effort, which is needed for the additional transport of the particles. This has not been assessed yet, but should be in the focus of future research.

The CFD model provides further information about physical effects and the detailed break-down of the losses. The thermal radiation losses predicted by the CFD model are significantly lower than from the Matlab calculations. Hence, the convection losses increase. Also, side wind increases the convection losses significantly, due to vortex generation. Installation of a wind shield may yield a significant reduction of the losses. This is a topic of actual research.

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