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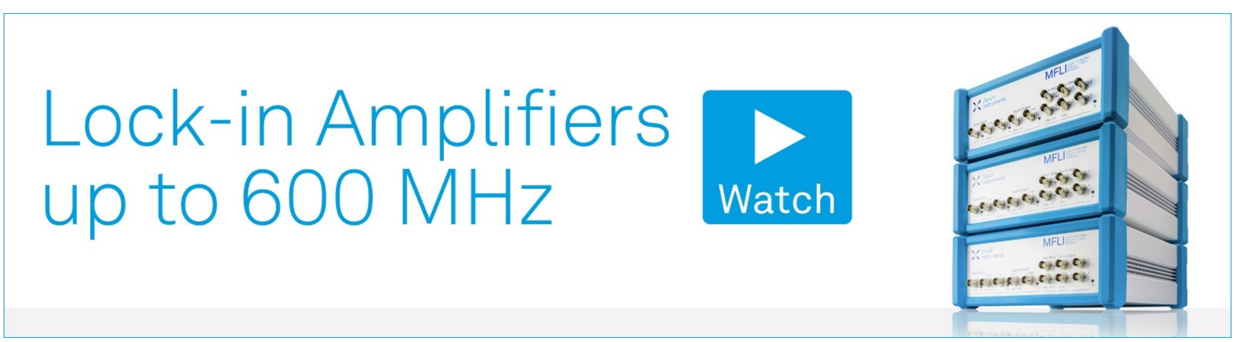
M. A. Moghimi, G. Ahmadi, M. Yang, and J. P. Meyer



Minimising Mirror Soiling of a PTC Plant by an Optimum Wind Barrier Design

MA Moghimi[1, a)], G Ahmadi[2], M Yang[3] and JP Meyer[1]

[1]*Clean Energy Research Group, Department of Mechanical and Aeronautical Engineering, University of Pretoria, Pretoria 0002, South Africa.*
[2]*Department of Mechanical and Aeronautical Engineering, Clarkson University, Potsdam, NY 13699-5725, USA.*
[3]*School of Mechanical and Power Engineering, Nanjing Tech University, Nanjing 211816, China*

[a)] Corresponding author: mohammad.moghimiardekani@up.ac.za.

Abstract. This study presents a simulation-based optimisation of a solid wind barrier surrounding a parabolic trough collector plant to minimise dust soiling on the plant mirror facets. The results of the presented simulation show that designing and constructing a barrier is one of the effective approaches to mitigate airborne particles and, consequently, to significantly reduce water consumption in solar plants for mirror cleaning. It is shown that an optimum solid wind barrier could deflect more than 86% of the particles that pass over the solar field with a small fraction of around 0.8% of airborne particles being deposited on the mirrors.

INTRODUCTION

The performance of a parabolic trough collector (PTC) plant depends on the reflectivity of mirror surfaces and, in particular, their surface cleanness (avoiding mirror soiling). According to Niknia, et al. [1], 1.5 g/m^2 dust deposition can reduce the instantaneous and average performance of the PTC plant by 60% and 37% respectively. Therefore, to keep the mirror clean, a relatively high level of water (0.2 to 1 litre of water per square metre of collector area for the most effective mirror-washing technologies) is used. This is particularly the case for desert areas that are perfect locations for concentrating solar power (CSP) plants due to high direct normal irradiance (DNI) and the available number of sunny days, but with little precipitation. For example, the Noor I PTC project in Morocco annually uses more than 36.5 million litres of demineralised water [2]. Therefore, the control of mirror soiling is not only an interesting contribution in the performance improvement of a CSP plant, but also saves a significant amount of scarce water in arid to semi-arid areas, which consequently decreases conventional CSP plants' levelised cost of electricity (LCOE) by favourably reducing the expenses of mirror cleaning.

A CSP plant is typically surrounded by a barrier wall, which ranges from a fence to a proper solid wall for security reasons and to determine the perimeter of the plant. The idea of this paper is to engineer the surrounding wall to act as a wind barrier as well. This will be one of the simplest and most economical approaches to deflect airborne particles so that they are deposited on the mirror surfaces. This approach is easy to implement, even in plants that operate without interruption. However, there are questions regarding the practicality and effectiveness of this approach. Therefore, this study focuses on the comprehensive optimisation of a solid wind barrier around a PTC plant to protect mirrors against dust soiling. In particular, this study tries to determine how effective an optimum wind barrier is in deflecting the airborne particle to pass over the solar field with the minimal deposition on the mirror facets. The following key questions must be considered when designing an optimum wind barrier for a PTC plant to minimise the soiling of the mirror facets: What is the optimum height of the barrier? What is the optimum length of the flap? What is the optimum angle of the flap? What is the optimum distance of the barrier from the first parabolic trough?

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DEFINITION OF PROBLEM LAYOUT, ENGINEERING TOOLS AND MODELLING

Problem Layout

The proposed field consists of a solid wind barrier with an inclined flap in the direction of the prevailing wind, along with six trough receivers with constant mirror pitch and aperture across the field. The barrier is erected at a certain distance from the first mirror surface. Figure 1 presents a schematic of the computational domain. In order to develop an optimum wind barrier, the design variables, namely the geometric parameters (barrier height (l_2), flap length (l_3), flap angle (θ) and barrier distance from the first collector (l_1)), have to be determined.

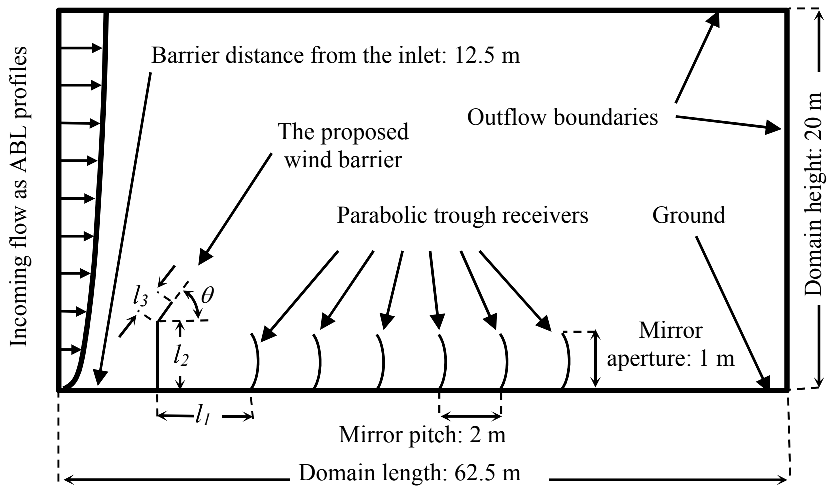


FIGURE 1. Schematic of the PTC field with a solid wind barrier

Optimisation Tool

ANSYS DX was used as the optimisation tool in this study. This is a commercial optimisation tool in ANSYS. The ANSYS platform created an integrated platform called WorkBench (WB), which allows researchers to interact with various engineering tools such as commercial computational fluid dynamics (CFD) codes and an optimisation tool (DX). This makes the optimisation process more robust, customised, user-friendly and easier, since the external interactions of different engineering tools with external third-party codes for the optimisation process are eliminated.

The optimisation simulation in WB is straightforward. In this study, the geometric design parameters (l_1, l_2, l_3 and θ) are introduced in ANSYS DesignModeler (DM) through geometry creation. The defined computational domain was then meshed using the ANSYS meshing tool. Afterwards, the meshed region was linked to the solver, ANSYS Fluent, as the CFD tool, where the optimisation goal parameter (total amount of particle depositions on all mirror surfaces) is defined. Finally, ANSYS Fluent is linked to the DX module, which is a response surface-based optimisation tool, for an optimisation process (see Fig. 2). The next sections describe the applied CFD modelling that was used to calculate the optimisation objectives.

CFD Modelling and Settings

The simulation of this study was carried out in ANSYS Fluent (version 18.1). To simulate the airflow and particle trajectories in the PTC field, an Eulerian-Lagrangian approach was used to evaluate the continuous airflow field (the Eulerian approach), followed by computing the Lagrangian particle trajectories by solving a one-way coupled discrete phase model (DPM).

It is assumed that the atmospheric boundary layer (ABL) flow is two-dimensional, steady-state incompressible airflow with constant properties at 300 K and no-slip velocity boundary conditions at all solid surfaces [3]. The airflow was simulated with the Reynolds-averaged Navier-Stokes (RANS) equations in conjunction with the k - ε turbulence model. Here the fully developed ABL velocity, k and ε profiles, as discussed by Richards and Norris [3], are imposed at the inlet of the domain, and the outflow boundary conditions were used on the top and right outlets of the domain (Fig. 1).

In addition, to simulate particle depositions on the solar field, the wind average velocity at the inlet ABL velocity profile was set at 10 m/s (see Fig. 1) and sand particles with diameters in the range of 25 μm to 250 μm were released at a height of 0.5 m to 3 m from the ground level at the domain inlet. These simulation entries simulate the physical observation of previous researchers regarding airborne deposition on mirrors of CSP plants [4–6]. The turbulent dispersion of particles, as well as the spherical drag force on the particles, along with following boundary conditions, were considered in this simulation: "escape" for the inlet and outflow, and "trap" for the solid walls of the domains.

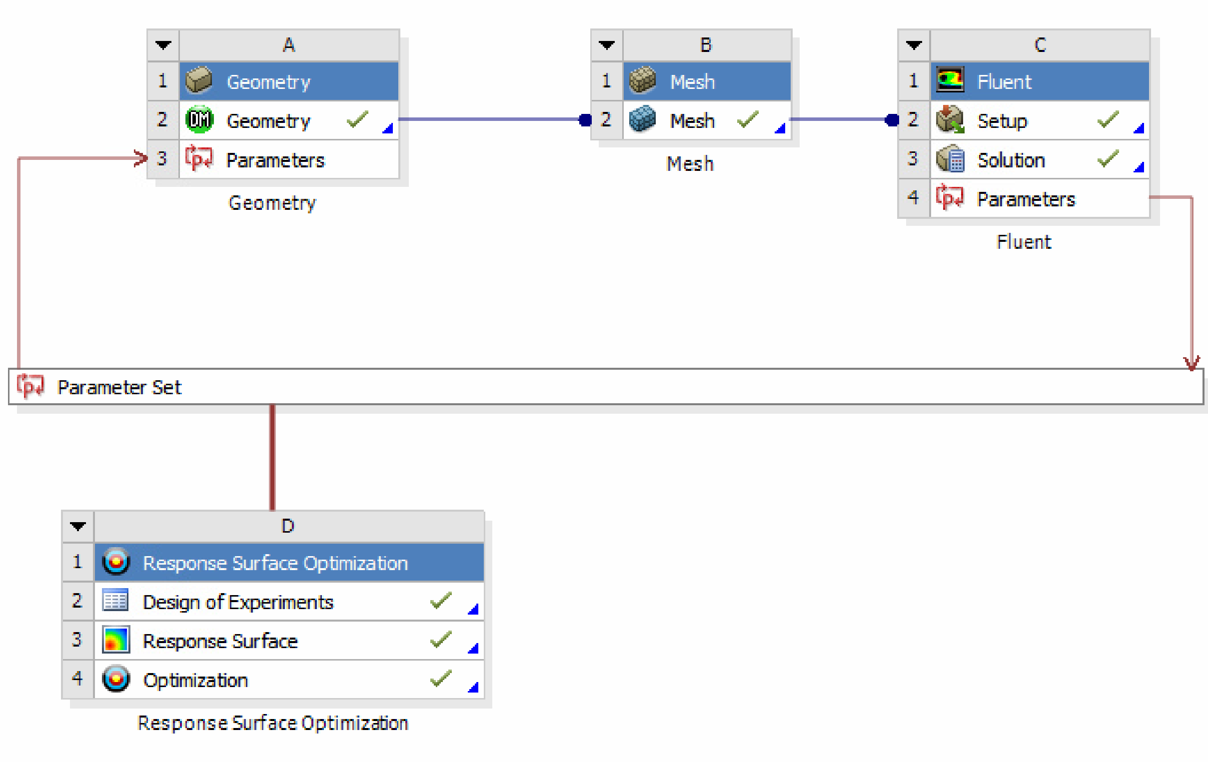


FIGURE 2. The schematics of the optimisation loop used, including meshing and flow simulations

OPTIMISATION PROBLEM DEFINITION AND SETTINGS

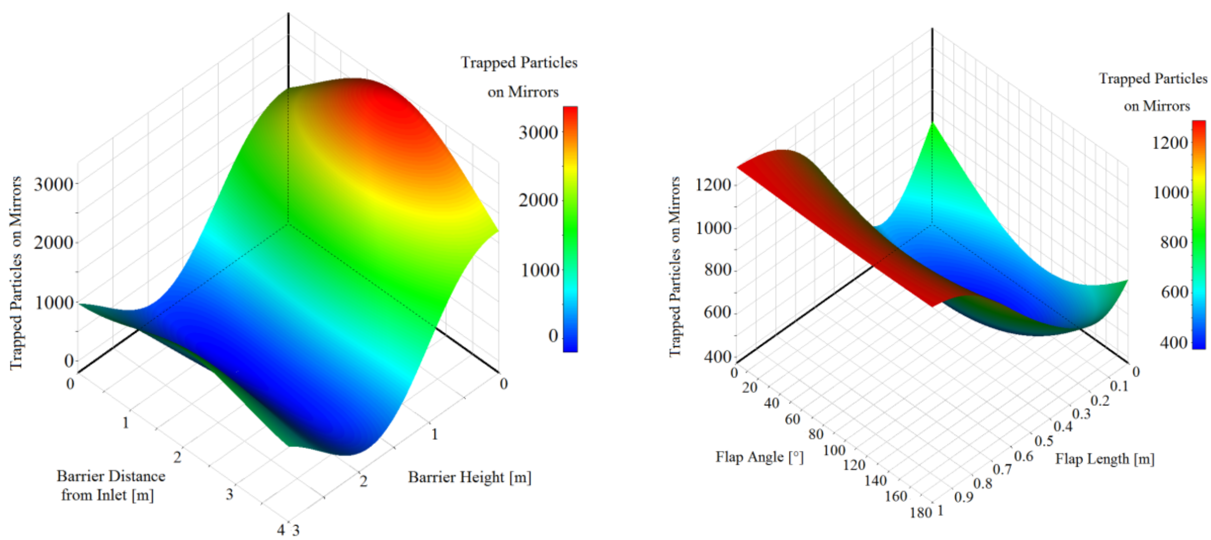
As noted before, the set of design variables of this optimisation study are wind barrier distance from the first collector (l_1), wind barrier height (l_2), flap length (l_3) and flap angle (θ). The lower and upper bound of these design variables are listed in Table 1. The goal of this optimisation study is to minimise the total amount of particle depositions on all mirror surfaces (called "trapped particles on mirrors" in this report) that is calculated in the CFD simulation.

The following features of ANSYS DX were used for the optimisation. The response surface method (RSM) was chosen for the mathematical optimisation. The design of experiments (DOE) was performed using a central composite design (CCD) algorithm that leads to the auto-generation of 25 design points according to combinations of the four independent optimisation parameters.

To construct the response surface in this optimisation study for each individual design point, ANSYS Fluent was run to extract the corresponding predefined optimisation goal ("trapped particles on mirrors"). Then, the construction of response surfaces was performed using non-parametric regression that led to the best goodness of fit for this problem. The determination of the optimum location on these surfaces was investigated by using the screening method followed by non-linear programming by quadratic Lagrangian (NLPQL) method.
For more information on the design point generations, RSM optimization approach, screening and NLPQL methods, optimization settings and in general optimization process, please consult Moghimi et al. papers [7-9].

RESULTS AND DISCUSSION

The optimisation of the generated response surfaces was converged after 823 iterations. The effect of different pairs of independent parameters on the optimisation objectives is presented in Fig. 3. It can be seen that the response surface is more sensitive to barrier height and flap length than flap angle and barrier distance from the first mirror (see the variation bounds of the optimisation goal versus each of the independent parameters in Fig. 3). Figure 3a shows that there is an optimum barrier height and barrier distance for constructing a barrier from the mirror field to minimise particle deposition on the mirror surface, which can be attributed to the sheltering effect of the wind barrier. In addition, there are optimum points for the flap characteristics (both height and angle). This could be due to their influence on the downstream vortices (see Fig. 3b). It's noteworthy that in Fig. 3b one may wonder how the number of particles varies with flap angle at zero flap length. This is attributed to the fact that the response surfaces are generated based on curve fitting of the results of design points (in this case 25 generated design points). Since very little number of design points was generated at zero flap length (only one case) and the other generated design points in the vicinity of the design point with zero flap length play role in curve fitting. Therefore, the generated response surfaces reach such unrealistic behaviour at zero flap length region.



(a) (b)

FIGURE 3. The response surface of objective versus independent parameters: a): barrier height and distance from the first mirror; and b): flap length and flap angle

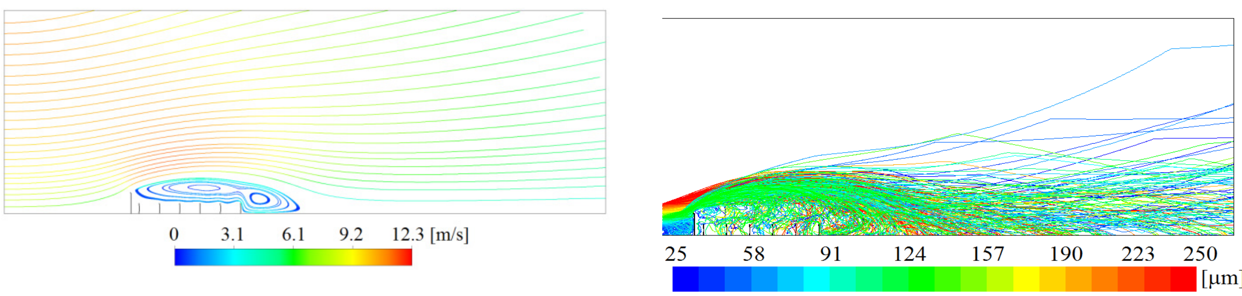
Table 1 lists the reported values for three utopian points by ANSYS DX among all optimal cases, along with the actual calculated values of the optimisation objective. To get the actual calculated results for the deposited particles onto the mirror surfaces in Table 1, the reported optimal set of parameters listed in this table were fed into the CFD model with 2 000 particle injections at the inlet.

TABLE 1. Candidate utopian points

Parameters (unit)	**Lower bound**	**Upper bound**	**First candidate**	**Second candidate**	**Third candidate**
Barrier distance from the first mirror (l_1) [m]	0.5	3.5	0.811	0.781	3.076
Barrier height (l_2) [m]	0.5	2.5	1.765	1.989	1.849
Flap length (l_3) [m]	0.05	0.5	0.286	0.119	0.141
Flap angle (θ) [°]	5	175	158	129	65
Objective definition	**Objective**		**Calculated**	**Calculated**	**Calculated**
Trapped particles on mirrors	Minimisation		206	178	235

For further investigation and to reduce the stochastic and statistical errors of the simulation, the second candidate listed in Table 1 was selected to track five million particles in the domain. The detailed CFD results (flow streamline and particle trajectories) for this candidate are displayed in Fig. 4. In this figure, only 400 particle paths are shown for a clear observation of particle trajectories. Figure 4a shows that the barrier creates an upward stream where the airflow is accelerated, from about 9.2 m/s at the tip of the barrier to 12.3 m/s over the mirror field (the yellow to red region in Fig. 4a). As illustrated in Fig. 4b, some smaller particles (below 100 µm to 150 µm in diameter) are more prone to either being captured by the recirculating region of the airflow beyond the wind barrier or carried to further distances in the domain by the accelerated mean airflow over the mirror field. These behaviours can be due to the low inertia of small particles. The more in detail discussion on the effect of separate particle sizes from small to large ones to the soiling of the mirror field, were discussed in the extended version of this conference paper [7]. However, for sake of brevity and due to the limitation in the length of this conference pare, have not been discussed in this document.

Table 2 summarises the fate of five million particles released in the domain. Interestingly, about 80% of the trapped particles (not escaped from the outlets) in the computational domain (2 749 991 from 3 440 563 particles) are deposited outside the mirror field (either before the barrier or after the last mirror). In other words, more than 86% of tracked particles (4 309 428 particles) did not fall in the mirror field domain at all. Interestingly, only about 0.8% of released particles (41 399 out of 5 000 000 particles) were deposited on the front of the mirrors. This proves the successful design of the barrier, which could effectively reduce mirror soiling and consequently the water consumption of the plant for mirror cleaning.



(a) (b)

FIGURE 4. The CFD results of the second candidate: a): streamlines coloured by velocity magnitude; and b): zoomed-in 400 particle trajectories coloured by particle size

TABLE 2. Particle fates in the domain for the second candidate for 5 000 000 tracked particles.

Total number of particles tracked in the domain (released from the inlet)	5 000 000
Total number of particles escaped from the domain	1 559 437
Total number of particles trapped in the domain	3 440 563
Total number of particles that fall in the mirror field (between the barrier and the last mirror, which includes the back and front of the mirror facets, as well as the ground between the barrier and the first mirror, and the ground between the mirrors)	690 572
Total number of particles deposited on the mirror facets	41 399
Total number of particles that fall out of the mirror field (the ground before the barrier, the ground after the last mirror and the barrier itself)	2 749 991

RECOMMENDATION TO FUTURE WORKS

This study was an initial step toward the feasibility study of wind barrier in soiling protection of CSP plants. As shown, in Fig. 1, in this study only 6 rows of PTCs (6 mirror facets) were considered for simulations and the results could not be generalized to large PTC fields. Although, this study (as the initial step of the feasibility study) proves the potential of wind barrier design in soiling protection of the CSP fields, further investigations with considering following aspects must be conducted to complete the feasibility study of wind barrier in soiling protection.

1) Conducting the similar study for a large and realistic plant, to reveal the dimension of the optimum case for a large plant
2) The dimension of the optimum wind barriers for a large plant must be normalized with, mirror aperture, mirror pitch and the distance of barrier to the first and the last mirror in the field. These normalization would assist the researchers to generalize the results to the other plants
3) To finalize the feasibility study and reveal the full potential of the wind barrier in a realistic site, the following complimentary studies on the proposed realistic site should be conducted:
    - A comparison study on mirror soiling of the site with no wind barrier with the site with the optimum wind barrier
    - An investigation on the effects of implementing the optimum wind barrier on the economic, optical and thermal characteristics of the proposed site.

CONCLUSION

Mathematical optimisation is shown to be a powerful tool that can be used to reach engineering goals. In this paper, the geometric parameters of a wind barrier that surrounds a PTC field was optimised to minimise the mirror soiling of the plant. Implementing an optimum wind barrier around a CSP field was shown to be a simple, effective and practical approach to significantly reduce the mirror soiling and water consumption of the solar plant. This will lower the plant's operational cost, as well as the cost of electricity production. This study can be used as a user's guide for future research to simulate, optimise and design novel wind barriers for other types of CSP plants.

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