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A CFD-Based Approach to Selecting a Concentrating Solar Thermal Plant Site Location Around a Ferromanganese Smelter

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Abstract

This paper outlines the initial phase of an investigation into the soiling effects of industrial dust on mirrors, and therefore heliostats, as a part of a larger EU Horizons 2020 project that is aiming to successfully demonstrate the integration of solar thermal heat into an industrial ferromanganese process. In addition to the need for a medium-term (2 years) soiling study, the need to be able to model and predict where dust will flow and deposit has been identified. It is foreseen that a generally applicable approach to modelling and predicting dust deposition ‘hot spots’ around an industrial processing plant, such as a smelter, will be useful in future where designers would want to be able to determine the best location, in terms of dust, to situate a concentrating solar thermal (CST) plant. The approach is based on micro-climate scale computational fluid dynamics (CFD) coupled with experimental validation work for dust deposition, mirror soiling and atmospheric boundary layer (ABL) flow characteristics.

Keywords: Solar Thermal Process Heat; Heliostat Soiling; Dust Deposition; Computational Fluid Dynamics; Environmental Fluid Mechanics; Dust Transport.

1. Introduction

The continued use of concentrating solar technologies is somewhat dependent on the expansion of its application in industries outside of power generation. One reason for this is the current low cost of utility scale solar photovoltaic power generation not only in comparison to CSP but also in comparison to traditional fossil fuel power stations. CSP still has a role to play in the energy mix where dispatchable power will be needed during peak and night-time hours because of its good thermal energy storage capabilities, but expansion to industrial energy applications can provide niche applications that cannot be met by solar photovoltaic technologies.

Potential examples of applications of concentrating solar technologies outside of power generation are being investigated for further investigation and study. One example of this is the integration of solar thermal heat energy, in the form of hot air, into the industrial beneficiation process of manganese ore smelting with which this paper is concerned. In this process the solar thermal heat energy will be used to pre-heat manganese ore to around 600 °C before being fed into the smelter, thus saving up to an estimated 20 % of electricity, 10 % of direct carbon dioxide emissions and in countries dependent on fossil fuel power plants for electricity significant amounts of indirect carbon dioxide emissions associated with power generation.

The authors of this paper are currently concerned with the feasibility of this pursuit in terms of the industrial dust that is expected to be a problem in the vicinity of one of these ferromanganese smelters. Considering that the wind blows in different directions, at different speeds, under different atmospheric stability conditions, it is conceivable that there would be a location around such a smelter where the least amount of particulate matter deposits throughout a typical wind year (TWY). This location of ‘least-dustfall’ would then logically be the most suitable location to situate a CST plant, considering that the heliostat field’s performance is directly linked to the cleanliness/reflectivity of the individual heliostats. The aim is to develop a methodology that takes all the parameters influencing dust dispersion into account and to then recommend a location in the vicinity of a smelter that would experience the least amount of dustfall throughout the year.

There are various empirical and semi-empirical models that have been developed by various authors. The model developed by Stovern et al. (2015) is an example of a model based on empirical relations, in the form of idealized particle trajectories, relative humidity and the inclusion of preferential deposition behavior when encountering different topographies, and physical simulations using a weather forecasting research (WRF) model

[1]. A site-specific tailored model such as the one described above is considered to take too long to construct for the considered application. CFD simulates the physical realities more closely, albeit at a higher computational cost.

This paper continues to describe the smelter of interest, computational domain and modeling approaches, along with the planned experimental work.

2. Description of Area of Interest

2.1. Smelter site under consideration

The smelter under consideration is the Transalloys silicomanganese smelter plant, located near Emalahleni, South Africa, with a maximum production capacity of 180,000 tonnes per annum, making it the largest in South Africa. The plant has five operational submerged-arc furnaces, totalling 150 MW [2].

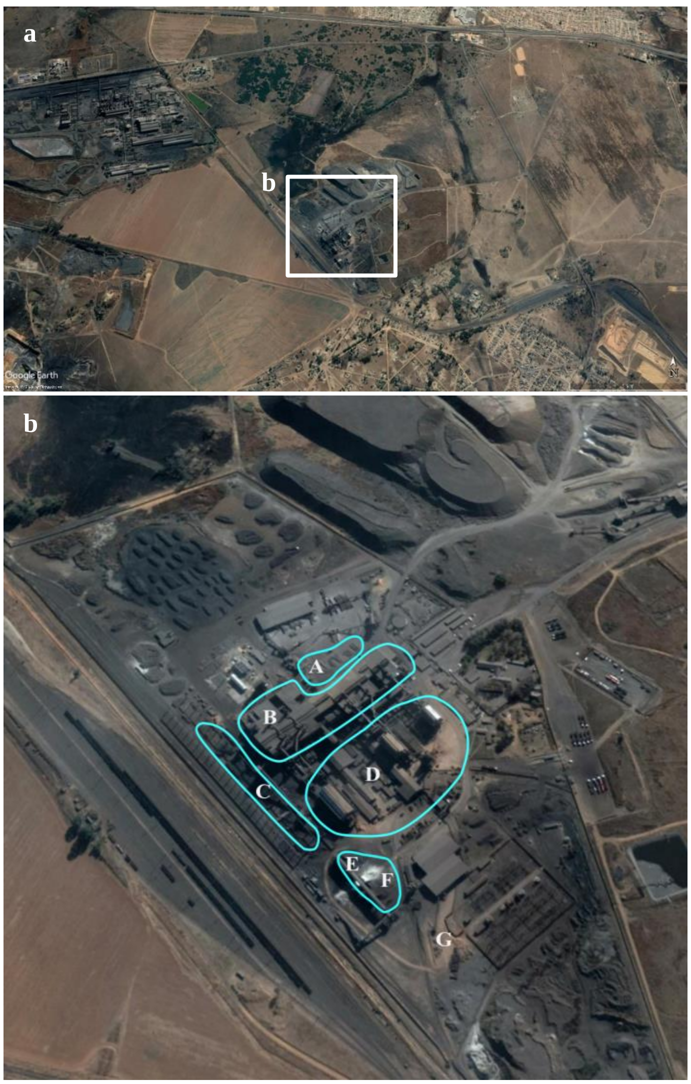

Figure 1. a) Transalloys silicomanganese smelter, b) Enlarged view of smelter, highlighting different potential sources of dust further explored in sub-section 2.2. Source: Google Earth.

Figure 1.a) shows the smelter under consideration. The plant sits atop a small hill, has human settlements to the north and south, with an inactive industrial site north-west of it.

2.2. Potential Dust Sources

Figure 1.b) highlights the different areas within the plant that inject dust into the atmosphere or have the potential to do so should the wind blow in a certain direction, above a threshold speed for that particular dust type. Representative samples were taken in each of these highlighted areas. These samples are shown, strewn on white paper, in the series of photos shown in Figure 2.

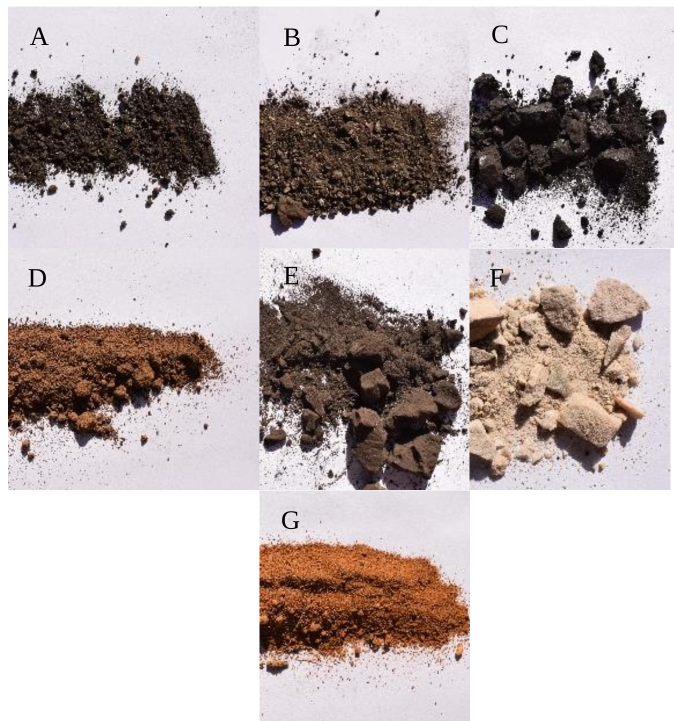

Figure 2. Dust samples representative of the different identified source areas.

From Figure 2 it is clear that each highlighted area contains different raw or processed materials, which have different chemical compositions and as such will have different particle-size and mass distributions. Differing physical properties results in these different kinds of dust behaving differently and depositing at varying locations in and around the plant, depending on the dust type and source location, as well as various atmospheric conditions. Because of this, chemical analysis will be done on the samples to determine the exact chemical compositions, which are known to be mainly – and are generated when:

A. FeO – Iron oxide dust fallout during tapping.
B. SiMn – Silicomanganese dust fallout during casting.
C. C – Carbon dust from handling high-carbon charcoal.

D. Baghouse dust – Mixture of A, B, and C after process.
E. MnO_x – Manganese ore dust resulting from handling.
F. SiO_2 – Quartz dust resulting from handling.
G. Local red sand – generated dust when drive over.

3. Computational Domain

3.1. Approach

CFD of wind flow over large land areas have become commonplace amongst scientists and engineers interested in studying natural phenomena and looking at things like pollution dispersion. This results from the growing increase in computational power along with decrease in cost, making it less expensive to obtain Reynolds Averaged Navier-Stokes (RANS) based solutions at scale, especially if many cases are to be considered. Large-Eddy Simulation (LES) is also becoming more accessible but is not commonplace as of yet because the establishment of best practice guidelines for the implementation thereof are still under development [3] and the computational cost is still often too high. The current methodology therefore aims to specifically use RANS-based simulations. For this approach Blocken and Gualtieri (2012) developed good practice CFD guidelines for evaluating environmental fluid mechanics (EFM) which will be used as guideline to this study [4].

3.2 Topography of the region surrounding the smelter

Near-field pollution and dust dispersion studies typically consider sources from 2 km up to 10 km upstream of the area under consideration [5]. For this study it was decided that considering and characterising sources up to 8km upstream would be appropriate. This is captured by the black dotted-line circle drawn around Transalloys, where the smelter is circled with a yellow dotted line, in Figure 3.

Within this area efforts will be made to characterise area sources and to appropriately discretise areas with different activities as seen in Figure 4. Since complex topography directly effects ABL flow turbulence characteristics, efforts have been made to obtain 50cm height resolution, by 2m horizontal resolution, digital elevation and digital terrain maps (DSM and DTM respectively) for the 8km radius area. DSMs provide topographical elevation data of the first reflected surface as a scanning instrument would see it from above, buildings and other unnatural solid surfaces are represented from the top, whereas DTMs are post processed to remove these unnatural features so that only terrain features are represented. Freely available Shutter Radio Topography Mission (SRTM) elevation data will be used for the rest of the 'outer-ring' terrain [6].

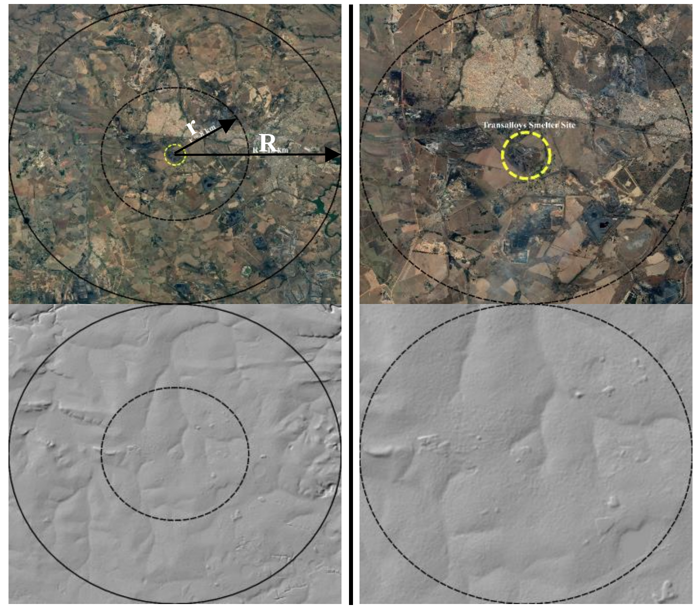

Figure 3. Larger 18km radius, labelled 'R', included in computational domain with accompanying DTM (left); 8km radius, labelled 'r', view of immediate surroundings to smelter with accompanying DTM (right).

3.3. Terrain roughness classification

The land cover and use of the region surrounding the smelter, followed by its simplification for terrain roughness modelling purposes, is shown in Figure 4.

Figure 4 shows an example of how the terrain coverage might be simplified. The terrain can be modelled implicitly or explicitly, where implicit modelling uses an aerodynamic roughness length, z_0, to capture the effects of terrain coverage such as grass, forested areas and tightly and loosely spaced urban areas for instance [7]. Explicit modelling is reserved for target areas of interest such as the smelter buildings and immediate surrounds of the smelter area.

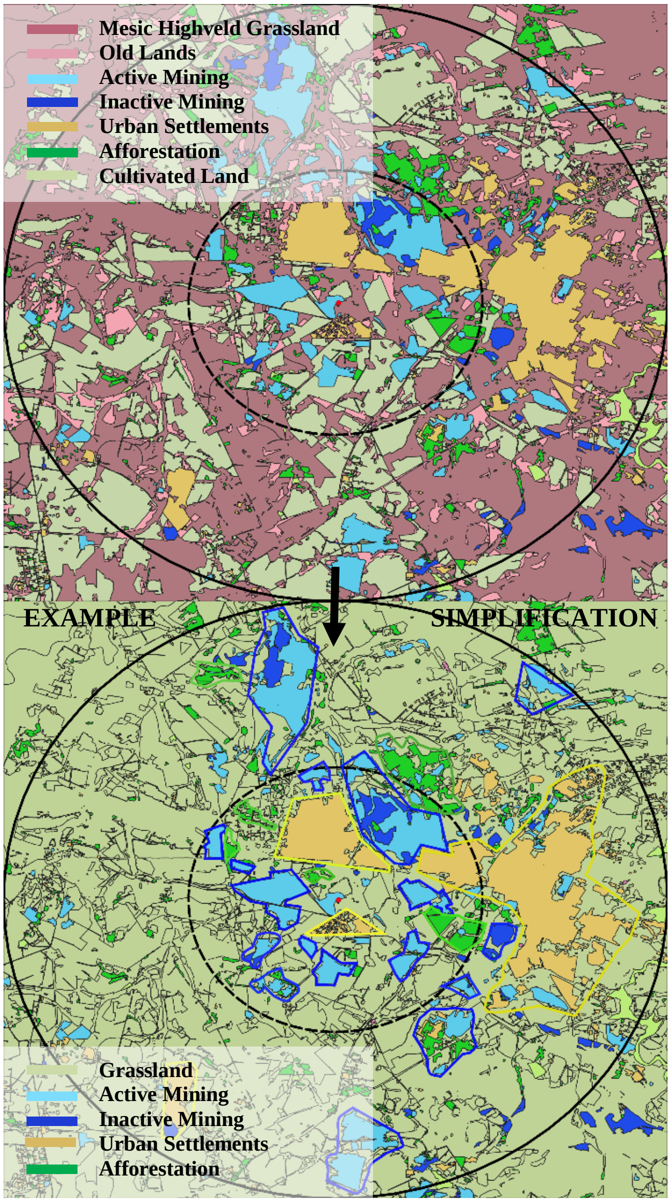

Figure 4. Land cover map of region surrounding smelter (top); simplification and grouping of land cover (bottom).

Table 1 shows the different terrain roughness lengths assigned to the different land covers found in the region shown in Figure 4, in accordance with [7].

Landscape description	Roughness length, z_0 (m)
Grassland (the combination of mesic Highveld grassland, old lands and cultivated land)	0.10 (roughly open)
Afforestation	0.50 (very rough)
Active mining	1.0 (closed)
Inactive mining	1.0 (closed)
Urban settlements	1.0 (closed)

Table 1. Assigned terrain roughness length as it pertains to the wider geographical region shown in Figure 4.

3.4. Wind flow directions

A typical wind study will look at 12 or more wind directions, this one will use 16 wind directions [4], as shown in Figure 5.

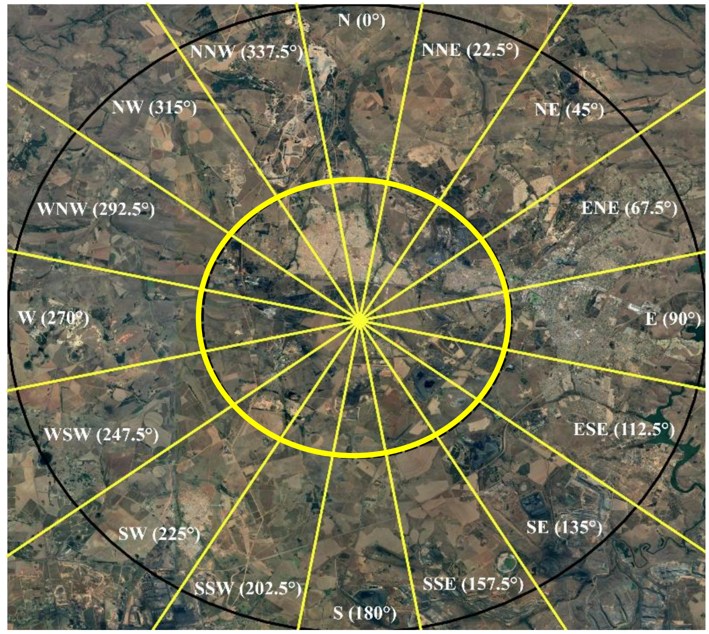

Figure 5. Wind flow directions to be considered and an indication of the study area (yellow circle).

The yellow circle shown in Figure 5 is the area of interest where dust dispersion and deposition will be closely looked at.

5. Measurement Campaign and Validation

5.1. Weather Station

A full meteorological research station has been installed just north of the smelter, a photo of the station is shown in Figure 6.

The station measures direct normal irradiation (DNI), diffuse horizontal irradiation (DHI), global horizontal irradiation (GHI), wind speed, wind direction, relative humidity, total rainfall, temperature, and barometric pressure. This stations data will be used as a point of reference for all other data points and outputs from the CFD results.

The station has a 10m wind mast which will be continuously logging data. This will be complimented by another portable wind mast with two ultrasonic anemometers, which will be used to characterise the ABL velocity profile. These two points of measure, along with other anemometers in the region will be used to help with validation.

Figure 6. GeoSUN meteorological research station installed at the Transalloys smelter, near Emalahleni.

5.2. Soiling Study

Many researchers have done soiling studies, looking at reflectivity degradation over time of heliostats and mirrors in desert and semi-desert environments. In recent years there have also been many studies investigating the effects of soiling on photovoltaic panels, both in desert and urban environments. A review by Costa et al. (2018) summarises these studies [8].

Studies looking at soiling of mirrors in industrial environments, and the effects of industrial dust on mirrors have not yet been performed. This is not surprising as it has been a priority of CSP plant designers to locate areas far away from any human activity, which is the case in a place like Upington, Northern Cape. In the experimental campaign of the current study, 32 mirrors, of A3 size, will be placed on steel stakes 2m above the ground at eight different locations around the plant in groups of four. The reflectivity loss of the mirrors will be measured as a percentage of the cleaned mirror surface on a weekly basis. The reflectivity will be measured using the device and method published in the investigations of Griffith (2014) [9]. The method is based on taking pictures of the soiled and cleaned surfaces and using averaged pixel intensity to arrive at reflectivity values. A diagrammatic representation of the reflectometer device is shown in Figure 7.

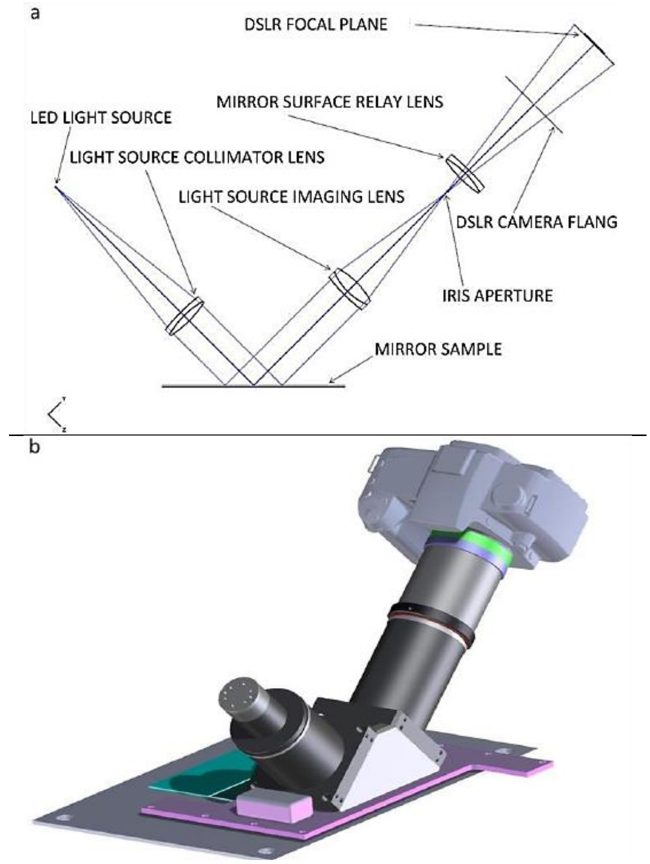

Figure 7. Labelled schematic representation of camera + reflectometer lens assembly (top), CAD of reflectometer (bottom)With permission from [9]**.**

5.3. Dust Deposition Study

Chemical analysis of the collected dust source samples are currently outstanding. Future work will compare dust samples collected to the source sample to determine the predominant origins of dusts.

The dust deposition study will be based on SANS 1137, itself a derivative of ASTM D1739 [10]. In this standard, a bucket is used to capture dust for later analysis. The bucket is surrounded by a windshield to regulate the capturing of dust particles. CFD simulations will be used to predict the influence of the wind shield on capturing different particle sizes based on modelled wind speeds. Dust buckets will be collocated with the mirror samplers, at eight locations around the plant.

Figure 8 shows flow patterns around the dust bucket, where it can be seen that the wind shield described in the abovementioned standard creates a stagnation region, thus resulting in a higher particle fallout and capture. This is an improvement upon previous dust bucket designs where many particles were not captured because of being re-directed by the mean flow.

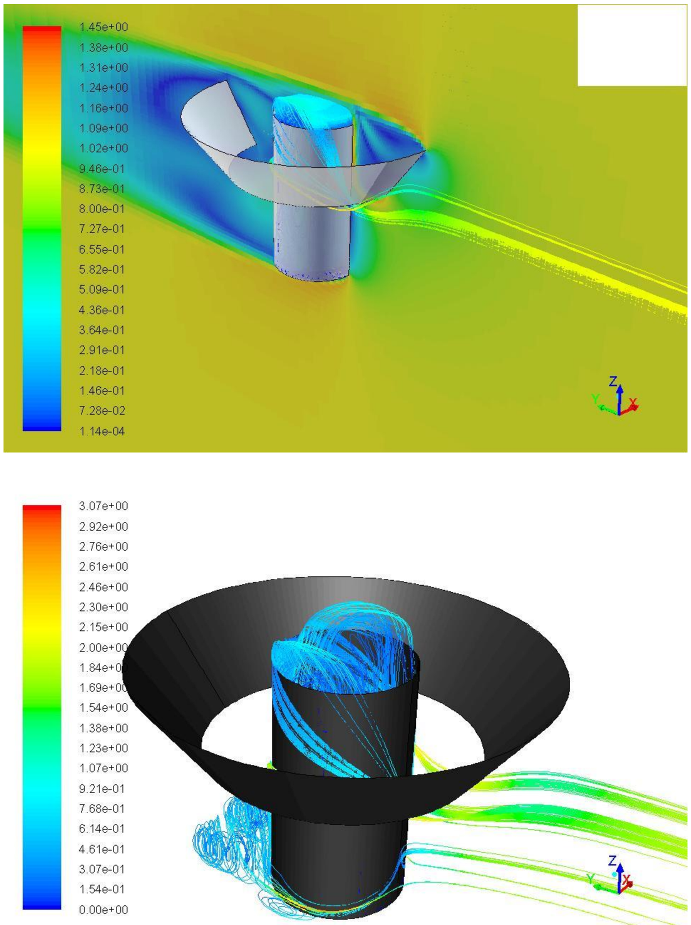

Figure 8. Flow pattern around dust bucket with wind shield. Velocity magnitude contours on central plane (top), 30 micron particles coloured by velocity magnitude (bottom).

6. Conclusion

Suitable methods for determining the best siting of a solar thermal plant in relation to a ferromanganese smelter have been identified. These methods include the creation of an appropriate CFD model and validating it with experimental results. The experimental campaign consists of mirror reflectivity degradation in an industrial environment, dust deposition studies, dust sample analyses, meteorological measurements, and ABL characterisation. The expected outcome is that the CFD simulation will produce dust deposition maps, and therefore heliostat soiling potential maps, of the study area which can be summated for the different wind directions and atmospheric conditions. It is expected that the ideal location of a CST plant next to, or nearby, an industrial processing plant would be in the location where the heliostat soiling potential is the least. Although the results from this study is still outstanding, the novelty of the application is of great interest to future industrial applications of solar thermal process energy. The description of this methodology will inform future publications which will focus on the results achieved.

Acknowledgements

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