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Annual Performance Optimization of a Linear Fresnel Collector in Pretoria, South Africa

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Abstract. This study presents a simulation based optimization study of a multi-tube trapezoidal cavity receiver of a Linear Fresnel Collector plant in Pretoria, South Africa. A comprehensive optimization study - an optical, thermal and economic optimization study - based on realistic simulations of these objective goals on an annual basis for such a plant is presented in this paper. This paper could be used as an applicable guideline for future researchers who work on the optimization of Concentrated Solar Power Plants.

INTRODUCTION

Linear Fresnel Collector (LFC) technology is one of the main types of linear concentrated solar power (CSP) technologies of which the development started in the late 1960s and is still ongoing. This is because of its advantages in comparison with other CSP technologies such as lower capital cost, easy and low maintenance, high ground utilization and so on. These advantages drew more attentions recently to this field and its optimization [1-5]. However, due to the definition of a variety of optimization objective goals, the results of existing optimization studies vary and sometimes contrast each other especially when the three key components, i.e., optical, thermal and economic performance are considered in isolation. For example Moghimi [6], in the literature study of his PhD thesis, discusses the contrasts between the results of a few optimization studies due to isolated single-discipline definitions in their optimization goals. Therefore, a comprehensive optimization study in which all three: thermal, optical and economic performance parameters of an LFC, are considered simultaneously was justified. Similar optimization studies were conducted by Moghimi [6-9] for ideal summer conditions.Those studies targeted to harvest the maximum daily solar energy (maximising plant optical efficiency throughout a summer's day), while minimising plant thermal heat loss (maximising plant thermal efficiency), as well as minimising plant cost (the economic optimisation of the plant) simultaneously. However, because of simplified or academic assumptions in those studies, generalization of the results to a specific location and considering itsannual performance, was not possible.

The current work addresses these shortcomings by considering a specific location, Pretoria, South Africa, as example, and considers the following.

1) The seasonal effect of the sun is incorporated by an accurate implementation of the sun's elevation angle (which varies between about 45° in winter to about 90° in summer for this location).

2) The DNI variation throughout a day is based on the location of a plant, taking into account that the DNI value not only varies throughout a day but it also throughout the year.

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3) A realistic sunshape is used for the specific location (instead of the pillbox profile of previous studies). This is coupled with more realistic optical errors of the reflecting elements

4) Finally, a single focal length is considered for all mirrors in the Fresnel array.

Therefore, this paper aims to present a comprehensive annual optimisation study of a Linear Fresnel Collector (LFC) plant with a trapezoidal multi-tube cavity receiver situated in Pretoria.

PRELIMINARY INVESTIGATIONS FOR REALISTIC ANNUAL OPTIMISATION STUDY

Before running an annual optimization of the plant, a few preliminary studies have to be conducted for the proposed site. These studies are: Direct normal irradiance (DNI) predictions, features of solar brightness profile, and optical error assumptions. The more realistic calculation of these will lead to a more accurate calculation of the annual optical performance of a plant. These are discussed in the following:

DNI Prediction: Due to the lack of long-term meteorological data at the proposed site (Pretoria, South Africa), the authors looked for the most appropriate parametric DNI models that can be applied in the optimisation study. To pick the most accurate model for the discussed location, four well-known parametric DNI models suggested in the literature, were chosen. Those models are: Iqbal Model C [10], ASHRAE 1972 Model [11], Modified ASHRAE 1972 Model [10] and ASHRAE 2013 Model [12] . To pick the most appropriate model for the prediction of DNI at the proposed site, the monthly DNI prediction of these models were compared with available meteorological data at the site (gathered since September 2013 from [13]). Comparisons of meteorological data with parametric models for sample of months are reported in Fig. 1. According to this study, the ASHRE 1972 Model, due to its simplicity and accuracy, was picked as the most appropriate DNI predication model for the optimization process.

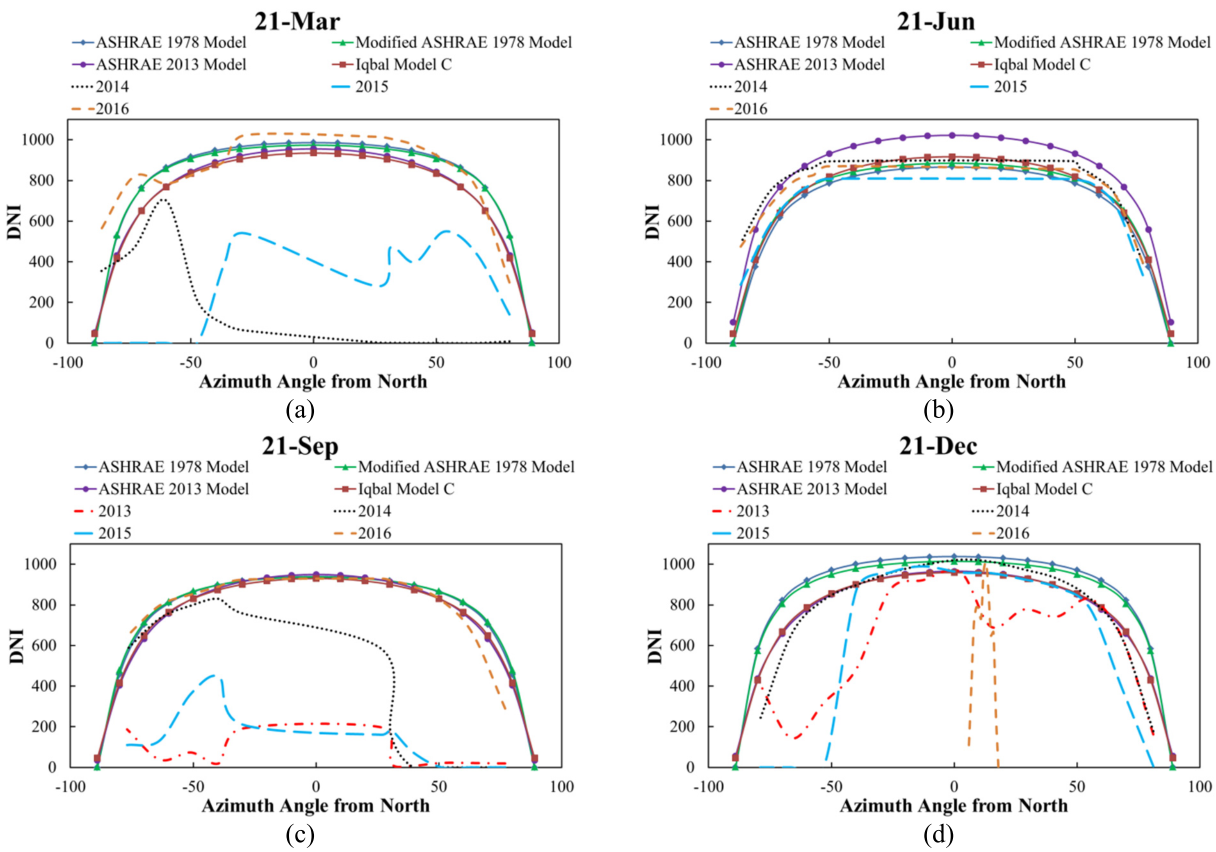

FIGURE 1. Sample of DNI comparison of parametric models with metrological data from [13] for University of Pretoria, station. (a) 21 April, (b) 21 June, (a) 21 September, (b) 21 December.

SunShape: In addition to DNI, the other import factor which plays an important role in the optical simulation of CSP is the solar brightness profile or Sunshape. Two common sunshapes which are often used (e.g. Moghimi et al. [6-9]) are pillbox and Gaussian distributions. According to [14], the Pillbox sunshape definition leads to an overestimation of concentration factors in CSP technologies while the Gaussian sunshape has a poor representation of reality. Therefore, there is a need for a more realistic sunshape definition. In 2002, Neuman et al. [15] proved that the DNI value is strongly related to circumsolar ratio profiles as empirically developed. These profiles were called CSR profiles and can more realstically define the sunshape. Table 1 lists the CSR bins that have the dominant probability in each DNI range. Therefore, in this study, based on the specific time of year, the DNI is calculated according to the suggested model as listed in Table 1.

TABLE 1. DNI distribution with CSR used for Pretoria

DNI [W/m^2]	**0-200**	**200-400**	**400-600**	**600-800**	**800-1000**	**1000-1200**
Profile Name	CSR40	CSR30	CSR10	CSR5	CSR5	CSR0

Optical errors: In addition to the aforementioned parameters, there is a range of error sources which influence the concentration of solar power on the receiver in an optical simulation. These errors include specularity, slope and tracking errors which were tset os 3mrad [16], 3 mrad [17], and 1mrad [18] in this study.

OPTIMIZATION PROBLEM

This study is a continuation of previous work by Moghimi et al. [7] and aims to improve it by considering more reliable and physical assumptions (sunshape and optical errors) in calculating the annual performance of a plant. The optimization process and analysis of optical, thermal and economic performance, as described in detail in [6-7], is applied to the general configuration of a multi-tube trapezoidal cavity receiver of an LFC. The independent and dependent variables, as well as upper and lower bound of those variables in the optimisation process, are listed in Table 2. SolTrace is used for the optical modelling of annual performance. To calculate the annual performance, for an indicating day of each month (21st of each month) 5 different transversal angles for every 18 degrees (18, 36, 54, 72, 90) were considered for that single day. Then, based on those defined sun positions on that day, the corresponding DNI, sunshape and optical errors as mentioned above, were calculated. Next, Soltrace is run to conduct the optical simulations of the 5 transversal angles to calculate the daily harvesting energy. Eventually by replicating the process for other indicating days of other months, the annual optical performance of the plant is calculated. The thermal model and the economic analysis of this study are respectively based on a radiation view-factor method and Mertin's work as described in detail in [7].

The optimization framework is automated in ANSYS Design Xplorer (DX) using Excel. Geometry design parameters and optimization objectives are introduced in Excel. The Excel module is linked to the DX module, specifically to its response surface-based optimization tool. In this study, 2583 design points were generated. In the response surface method optimization, the objective goals per each design points are calculated to construct a response surface through the results. Eventually, based on the definition of objectives on the constructed response surface, the optimum multi-objective solution of the problem is found.

In this study, for calculating the annual performance of each design point, 60 separate ray-tracing simulations (5 simulations per each indicating day in a month throughout a year) are conducted in SolTrace. In other words, 154 980 separate ray-tracing simulations were performed in the entire process of optimization (60 ray traces for the annual simulation of 2583 design points).

RESULTS AND DISCUSSION

The convergence of the optimization was obtained after 4 712 iterations on the combined response surfaces with a higher importance for the annual solar power objective and a default importance for the other objectives. Among all the feasible Pareto optimal cases, the values of three utopian design candidates were automatically presented by ANSYS DX. The suggested utopian points are reported in Table 2.

According to the results of objectives, the first candidate was chosen as the mathematical optimum case for further study. However, the inlet parameters of the suggested candidate design point were not of practical use for fabrication of a plant. Those data mathematically lead to an optimum point but from the feasibility viewpoint, those results are beyond tolerances of manufacturing process or not available in market (e.g. pipes in the market are available in certain dimensions). Therefore the results of 1st candidate are presented in practical values, under the feasible optimum case column in Table 2. The final configuration of the plant is displayed in Fig.2.

Finally, the results of the optical simulation of the feasible optimum case throughout a year are presented in Fig. 3. The reason of the kink low value at 90° in daily absorbed curve shown in Fig. 3 is due to the fact that at that sun position, the receiver cavity blocks the central mirrors of the LFC field (see Fig.4b).

TABLE 2. Objective and parameters range definition as well as calculated utopian candidates and feasible optimum case. The parameters in this table are defined in Fig. 2.

Independent parameters	**Lower bound**	**Upper bound**	**1st Candidate**	**2nd Candidate**	**3rd Candidate**	**Feasible Optimum Case**
Number of mirrors - N_m	10	50	12	12	24	12
Mirror width - W [mm]	100	1000	100.64	954.22	950.78	101
Mirror gap - G [mm]	10	1000	11.532	570.82	172.16	12
Cavity mounting height - H [m]	5	20	5.0372	10.804	8.6213	5.037
Tube radius - r [mm]	10	30	10.439 (20.878)	13.83 (27.66)	13.846 (27.692)	10.67 (21.34)
Tube gap [mm]	1	4	1.006	1.035	1.035	2
Tube bundle offset from cavity top wall - d [mm]	25	50	25.001	31.115	31.115	25
Cavity angle - θ [degree]	50°	90°	50.056	50.697	50.697	50
Cavity depth - h [mm]	100	150	100.39	149.64	149.61	100
Optimization objective	**Objective**		**Predicted**	**Predicted**	**Predicted**	
View factor of tube bundle [m]	Minimization		0.13088	0.00983	0.00741	
Plant cost factor	Minimization		739.01	6364.5	3110.1	
Annual solar power [W]	Maximization		5.3194E6	1.547E6	1.165E6	

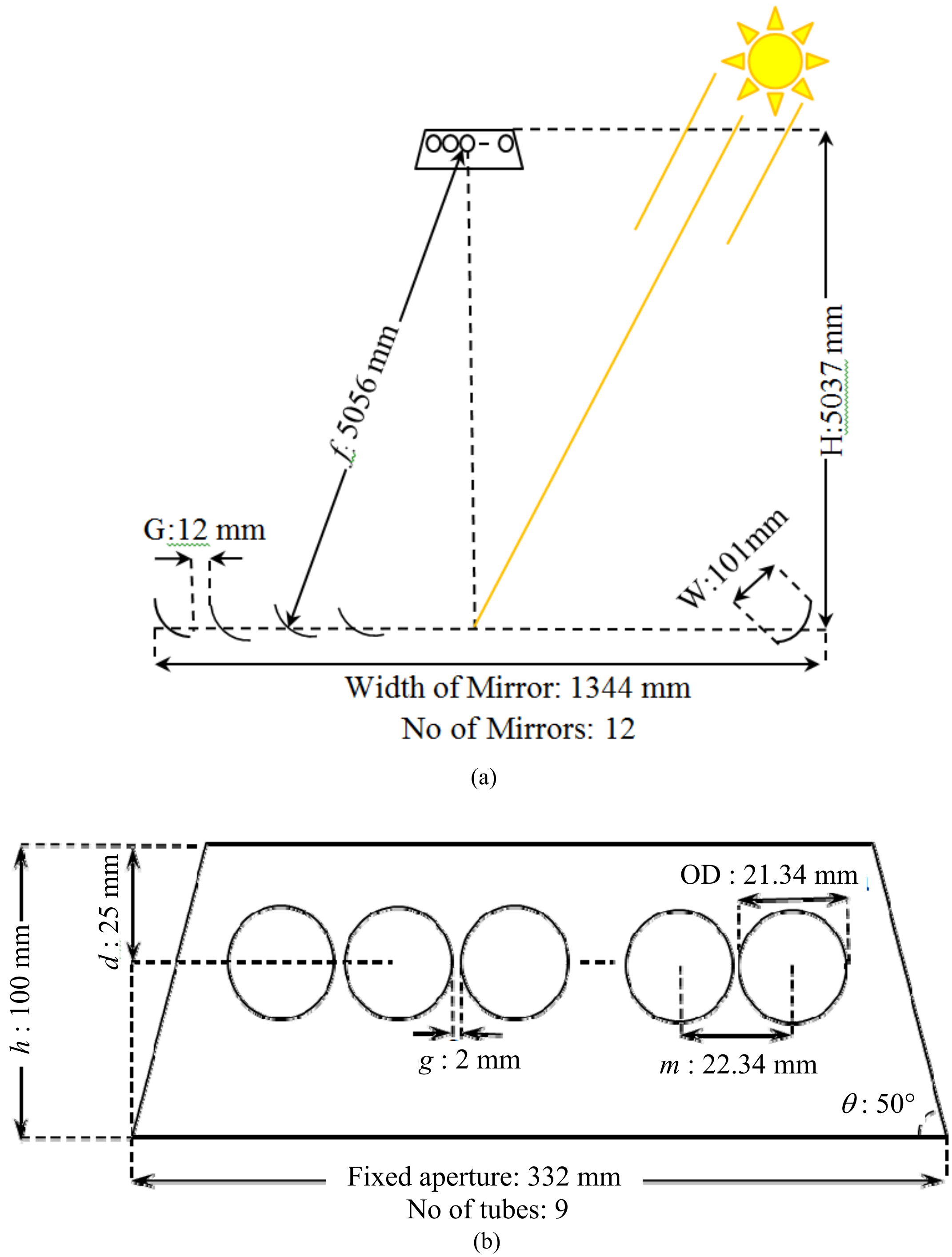

FIGURE 2. The schematic sketch of the entire feasible optimum LFC collector. (a) The collector, (b) The cavity zoom-in.

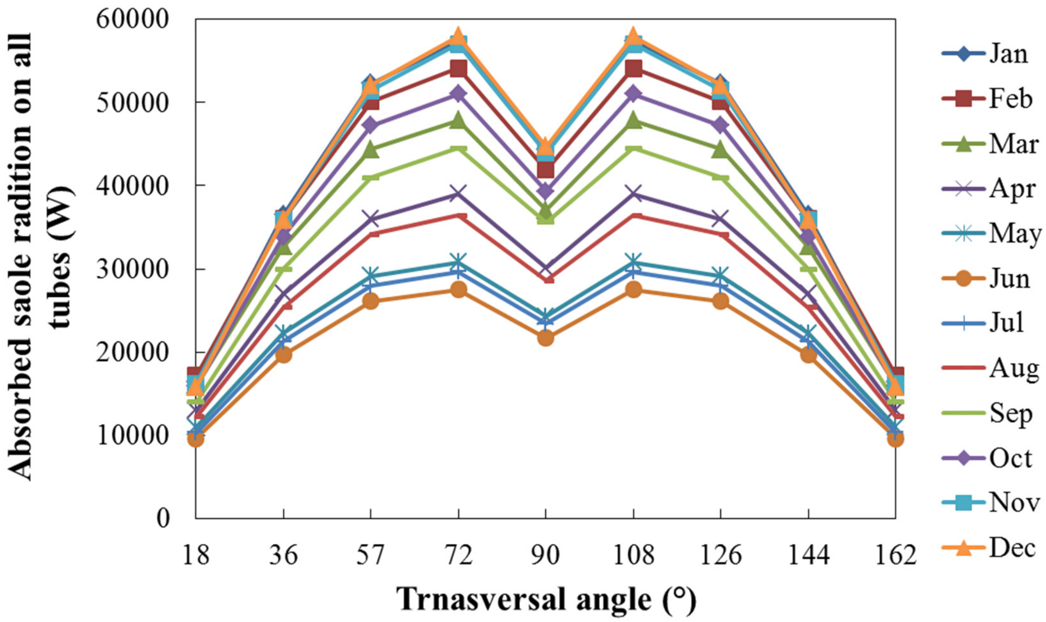

FIGURE 3. Daily absorbed solar radiation curves throughout a year. These curves present the optical performance of feasible optimum design point on the indicating day (21st) of each month.

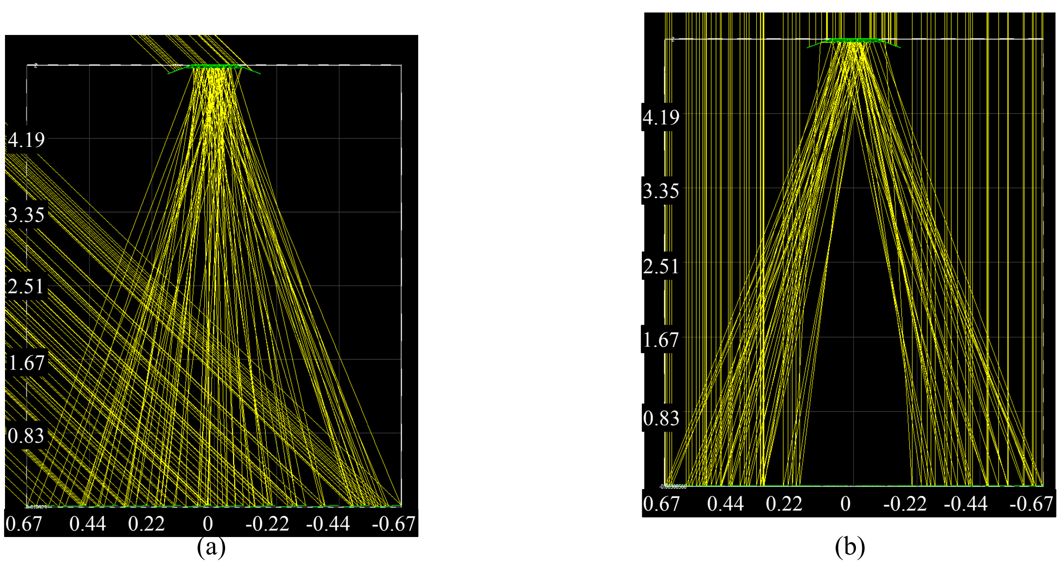

FIGURE 4. Ray tracing of the proposed optimum collector in January for two transversal angles a) 57° b) 90°. The figure is not scaled.

CONCLUSION AND FUTURE WORKS

Mathematical optimization proved itself as a powerful engineering tool in optimizing engineering goals. In this paper, an optimization investigation on an LFC plant with a multi-tube trapezoidal cavity receiver was conducted to find the most appropriate collector with minimum constructional cost and expense, highest annual solar absorption power, as well as minimum thermal losses from the cavity considering annual performance at a specific location.

The presented approach in this paper can be applied to the other CSPs plants with slight modifications.

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