Energy Conversion and Management 95 (2015) 1–9

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Optimization of heliostat field layout in solar central receiver systems on annual basis using differential evolution algorithm

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ARTICLE INFO

Article history:
Received 16 October 2014
Accepted 30 January 2015
Available online 21 February 2015

Keywords:
Annual optimization
Differential evolution algorithm
Genetic algorithm
Heliostat field layout system
Solar power tower
Solar central receiver system

ABSTRACT

Optimization of a heliostat field is an essential task to make a solar central receiver system effective because major optical losses are associated with the heliostat fields. In this study, a mathematical model was developed to effectively optimize the heliostat field on annual basis using differential evolution, which is an evolutionary algorithm. The heliostat field layout optimization is based on the calculation of five optical performance parameters: the mirror or the heliostat reflectivity, the cosine factor, the atmospheric attenuation factor, the shadowing and blocking factor, and the intercept factor. This model calculates all the aforementioned performance parameters at every stage of the optimization, until the best heliostat field layout based on annual performance is obtained. Two different approaches were undertaken to optimize the heliostat field layout: one with optimizing insolation weighted annual efficiency and the other with optimizing the un-weighted annual efficiency. Moreover, an alternate approach was also proposed to efficiently optimize the heliostat field in which the number of computational time steps was considerably reduced. It was observed that the daily averaged annual optical efficiency was calculated to be 0.5023 as compared to the monthly averaged annual optical efficiency, 0.5025. Moreover, the insolation weighted daily averaged annual efficiency of the heliostat field was 0.5634 for Dhahran, Saudi Arabia. The code developed can be used for any other selected location.

1. Introduction

Concentrated solar power (CSP) technologies, such as parabolic trough collectors, Fresnel collectors, solar dish collectors, or the heliostat field systems (the solar central receiver systems) are promising sources of energy production. Innovative researches are being carried out on all of these technologies for performance improvement and cost reduction. New designs using ray tracing simulations for the trough collector [1] and Fresnel collector for increasing the power output or reducing the manufacturing cost [2] are examples of such innovative research. Another example is multi objective optimization to improve the output power and performance of a solar dish integrated with a Stirling engine [3]. The need to develop CSP technologies is tremendous to overcome the significant energy demands and fossil fuel depletion. Therefore, pioneering and ground breaking researches are being carried out to optimize solar energy utilization. Heliostat field layout systems have recently started receiving spotlight due to the potential for higher efficiency and cost reduction [4]. Hence, these systems are expected to be the leading technology among all other (CSP) systems [5].

Heliostat field layout optimization is a complicated and tedious process in which thousands of heliostat coordinates have to be taken into account for achieving accurate results. An improved mathematical model for the optimization of the heliostat field layout on annual bases has been proposed in this study. The optimization is carried out using an advance evolutionary algorithm, named differential evolution.

Numerous studies were conducted to improve the performance parameters of the solar central receiver systems. One of the main distinguishing features of this technology is that it can attain a high temperature at the receiver. Thus, a high efficiency of the integrated thermodynamic cycle for power production can be obtained. Due to these factors, solar towers provide an opportunity to increase the capacity factor by using thermal storage system. Cost and performance analysis of different storage types for concentrated solar power production like packed bed and structured thermocline thermal energy storage were performed by Strasser and Selvam [6] and in a similar manner performance and cost analysis was carried out for latent heat thermal energy storage by Nithyanandam and Pitchumani [7]. In a different study, sizing analysis of the storage

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http://dx.doi.org/10.1016/j.enconman.2015.01.089
0196-8904/

Nomenclature

$\overset{\frown}{d}_{sun}$	unit vector pointing toward the sun
$\overset{\frown}{d}_{n}$	unit normal vector of the heliostat
DH	heliostat diagonal, m
DM	characteristic diameter, m
DR	receiver diameter (cylindrical), m
$dsep$	extra security distance, m
f_{at}	atmospheric attenuation factor
f_{itc}	intercept factor
f_{sb}	shadowing and blocking factor
f_{at_annual}	annual atmospheric attenuation factor
f_{sb_annual}	annual shadowing and blocking factor
f_{itc_annual}	annual intercept factor
HFLODE	heliostat field layout optimization using differential evolution
LH	height of the heliostat, m
LR	receiver size, m
LW	width of the heliostat, m
n_d	a day in the year
$Nhel_i$	number of heliostats in ith zone
$Nrows_i$	number of rows of heliostats in ith zone
R_i	radius of first row of heliostat of ith zone, m
S_{rec}	slant distance between the heliostat and the central receiver, m
THT	tower optical height or aim point height, m
wr	ratio of heliostat width to heliostat height

List of Greek symbols

α_s	solar altitude angle
$(\cos\omega)_{\_annual}$	annual cosine factor
δ	solar declination angle
$\Delta\alpha z_i$	azimuthal spacing between adjacent heliostats in ith zone
ΔR_{min}	minimum radial distance between the rows of heliostats, m
ΔR_i	radial distance between the rows of heliostats in ith zone, m
η_{maa}	monthly averaged annual optical efficiency of the heliostat field
η_{daa}	daily averaged annual optical efficiency of the heliostat field
η_{iwaa}	insolation weighted daily averaged annual optical efficiency of the heliostat field
γ_s	solar azimuthal angle
ω_s	solar hour angle
ω	incidence angle
ϕ	latitude angle
ρ	reflectivity of the heliostat
σ_{tot}	total standard deviation on the receiver plane
σ_{bq}	standard deviation of beam quality error
σ_{ast}	standard deviation of astigmatic error
σ_t	standard deviation of tracking error
σ_{sun}	standard deviation of sunshape error

tank for phase change material storage was performed by Xu et al. [8]. These are few of the examples of research for cost and performance improvement in the thermal energy storage field to obtain a uniform flux output from CSP technologies for different applications.

Energy analysis of a solar tower power plant without an energy storage was performed by Benammar et al. [9]. In their study, the solar tower was coupled with a steam Rankine cycle and the whole system was divided into four main subsystems, namely the heliostat field subsystem, the cavity receiver subsystem, the steam generation subsystem, and the power cycle subsystem. However, the heliostat field efficiency was taken as a constant value for the sake of analysis in their study, which did not provide the real performance of the system. Lipps [10] proposed a cell wise approach for the optimization of a heliostat field. Using this approach, the heliostat field is divided into cells, and the optimization of each cell is based on the costs and performance, giving the radial and azimuthal spacing in each cell. These values are fitted over the field, and applied to give the location of the heliostats in the layout.

In a study by Zhu and Lewandowski [11], a Matlab code was used to develop a new approach for the calculation of intercept factor for parabolic trough collectors. In their study, it was claimed that the suggested approach can be applied to other CSP technologies such linear Fresnel collectors or the central receiver systems. A code named as HFLCAL was developed by Schwarzbözl et al. [12,13]. A set of assumed heliostat positions are optimized and the performance of these heliostats is calculated by their code. The code computes the intercept by describing the reflected image of each heliostat as a circular normal distribution, and thus the intercept is described by an analytical function.

A code based on the discretization of the heliostat surface into cells was suggested by Noone et al. [14]. This code considered a non conventional biometric pattern for the heliostat field layout for computing the annual performance. Consequently, of using this new pattern, better annual efficiency was achieved; nonetheless, in a full optimization process, which includes a large number of heliostats, it can be time consuming due to the implementation of a discretization approach, especially if the intercept is calculated locally for each cell.

Another research code with the same approach of discretizing the heliostat surface into cells was developed by Leonardi and D'Aguanno [15], named as CRS4-2 (Research software for central receiver solar system simulations). The center of these cells is projected following the sun and the receiver for the calculation of the shadowing and blocking factor, respectively. Optical performance of a heliostat field of diverse geometrical parameters can also be calculated using this code. However, this code does not consider the calculation of the intercept factor.

Besarati and Goswami [16] performed optimization of the same heliostat layout as was done by Noone et al. [14] in their research. Nevertheless, instead of using a discretization approach for the calculation of the intercept factor and the shadowing and blocking factor, other approaches were implemented. The intercept factor was calculated using the HFLCAL [12,13] model. On the other hand, a new technique was developed for the calculation of shadowing and blocking factor, using the Sassi [17] procedure, which reduces the computation time. In a different study, Besarati et al. [18] used a genetic algorithm to determine the optimal flux distribution on the receiver surface of a solar tower. This was achieved by minimizing the standard deviation of flux density distribution by changing the aiming points of individual heliostats. The HFLCAL model was used for the calculation of the flux density. The results indicated that by using this approach, the maximum flux density on the receiver surface is reduced by a factor of 10 and formation of local hot spots can be avoided.

The Chinese Academy of Science developed a new code called HFLD (Heliostat Field Layout Design) [19,20]. Using their code, the optimization of the heliostat field is based on the receiver