Applied Energy 148 (2015) 282–293

Contents lists available at ScienceDirect

Applied Energy

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

Geometric optimization on optical performance of parabolic trough solar collector systems using particle swarm optimization algorithm

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HIGHLIGHTS

- It is to develop an optimization method and model for PTCs based on MCRT and PSO.
- A MCRT runtime reduction checking method is proposed firstly as it is very critical.
- The runtime reduction method is checked itself using well known statistical indices.
- A preliminary PSO–MCRT optimization analysis is carried out for an existing PTC.
- Comparation results show that the proposed PSO–MCRT model is feasible and reliable.

ARTICLE INFO

Article history:
Received 5 February 2015
Received in revised form 16 March 2015
Accepted 16 March 2015

Keywords:
Parabolic trough solar collector
Optical performance
Geometric optimization
Runtime reduction method
Monte Carlo ray-tracing
Particle swarm optimization

ABSTRACT

In this paper, an optimization model on optical performance of parabolic trough solar collector (PTC) systems is developed, based on the particle swarm optimization (PSO) algorithm and the Monte Carlo ray-tracing (MCRT) method. Since the computing time of a single MCRT simulation is always very critical to the whole optimization process and even to the feasibility of the optimization analysis if it is very time-consuming. Therefore, a MCRT runtime reduction method (RRM) was firstly proposed, by making a reasonable trade-off between the computational accuracy and the computing cost. Subsequently, the RRM was checked using well known statistical indices, due to the random number generation in the MCRT simulation and the statistical nature of the MCRT methodology. It is very significant that the corresponding calculation amount and computing time of a PTC MCRT simulation reduce by orders of magnitude and thus make the whole population-based PSO optimization process relative much feasible. Then a preliminary PSO–MCRT optimization analysis was carried out for an existing PTC system with known optimal optical performance, as it can be used to compare with the optimization results directly and thus to validate the PSO–MCRT optimization model. It is revealed that optimization results agree well with the reference data (Cheng et al., 2014), proving that the PSO–MCRT method and model used in the present study are feasible and reliable. In addition, error analysis and some further studies based on this proposed model are also discussed.

1. Introduction

The limited supply of fossil fuels and the negative impact of carbon dioxide emissions on the global climate change dictate the increasing usage of renewable energy sources. Efficient utilization of solar energy, especially the concentrated solar power (CSP) technology with concentrating solar collectors (CSCs) for harnessing the generally diffused low-density solar energy, is increasingly being the most likely candidate for providing the majority of this renewable energy [1–5]. Along the main four commercially available CSP technologies (i.e., solar tower or central receiver system, parabolic trough, linear Fresnel and dish-Stirling engine) [6–8], the parabolic trough solar thermal power (PTSTP) system is currently the most mature, lowest cost and widespread technology for large-scale exploitations of solar energy [9,10]. However, its cost is still more expensive than that of the conventional fossil fuel power plants [10–12]. To obtain a much lower electricity generation cost of PTSTP systems, further component developments and performance improvements are quite necessary [13]. Since the parabolic trough solar collector (PTC) subsystem is the main part of the PTSTP system, it is important to pursue an optimal design or parameter optimization to get significant performance

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http://dx.doi.org/10.1016/j.apenergy.2015.03.079
0306-2619/

Nomenclature

a	the aperture width (m)
c_1, c_2	acceleration factor
d	dimension number
d_{ai}	inner diameter of absorber tube (m)
d_{ao}	outer diameter of absorber tube (m)
d_{gi}	inner diameter of glass cover (m)
d_{go}	outer diameter of glass cover (m)
f	focal length (m)
g_{best}	global best position
l	active receiver length (m)
MAPE	mean absolute percentage error
N_d	number of possible decision variables
N_{last}	lasting number of successive iterations
N_{max}	total number of iterations
N_o	ideal surface normal direction
N_p	population size
N_{ray}	total number of photon packets
N_s	actual surface normal direction
p_{best}	personal best position
$q_{SR,in}$	total incident solar radiation (kW)
$q_{u,ab}$	absorbed solar energy (kW)
RMSE	root mean square error
r_1, r_2	random number
t	iteration number
v	particle velocity
V_{max}	clamped maximum velocity
w	inertia weight
x	particle position

Greek symbols

α_a	absorptivity of the absorber
χ	constriction factor
ε_m	relative error (%)
φ_m	the rim angle (°)
η_o	the optical efficiency (%)
ρ_r	reflectivity of the reflector
σ_s	surface error (mrad)
σ_{sd}	standard deviation
σ_t	tracking error (mrad)
τ_g	transmissivity of the glass cover

improvements of PTCs, as well as to develop efficient optimization methods and powerful tools.

Optimization in engineering design (such as the solar thermal applications) has always been a subject of interest to engineers and researchers. Many significant optimization studies on various kinds of solar systems have been carried out [14,15], such as optical, thermal, thermodynamic, exergetic, economic, exergoeconomic, thermo-economic and geometric optimizations on solar air heaters, solar flat-plate collectors, solar water systems, solar stills, concentrating solar collectors, thermal energy storages, solar power plants, photovoltaic systems, hybrid solar systems, passive solar designs and even solar radiation data or energy supply–demand estimations. Various optimization techniques either deterministic or stochastic to achieve these objectives have been implemented. More detailed reviews of optimization studies on solar thermal applications can be found in Refs. [14–17]. Three important search and optimization methods presented in literature are calculus-based, enumerative (including trial-and-error and univariate parametric studies) and stochastic methods [18]. The traditional calculus-based or gradient-based methods generally require a continuous function with existing derivatives that normally may be too restrictive in reality. They are usually restricted to local maximum or minimum but quite fast, depending strongly on the initial parameter vectors. The enumerative methods search the best solution using one-by-one calculation, which may be not efficient for problems of larger number of decision variables and much wide search spaces. Stochastic techniques, such as the genetic algorithm (GA), the particle swarm optimization (PSO) and the simulated annealing (SA), have evolved from the restrictions of these traditional classical or deterministic optimization methodologies [15,19]. They have nature of randomly searching, which enables them to approach the global optimum or near optimum and prevents them from trapping at a local optimum [20]. Significant successes have been achieved even though long computational times are often reported. However, researchers now can deal with real-life problems based on these algorithms that in the past were thought to be unsolvable, thanks to continuous developments and advances in the computer hardware and software [14].

For PTC systems studied here, the modeling and optimization on its optical performance exactly play an important role in predicting and improving the total collector efficiency (including the optical and the consequent thermal performance). Therefore, efficient optical modeling methods and performance optimization algorithms with the help of capable optimization techniques are necessity. There are many significant optical models published, which are developed to predict the concentrated solar flux distributions or estimate the optical performance of PTCs. Some of them are usually based on quite simple but quick geometric analytical methods, integral methods and non-imaging optics techniques (e.g., the edge-ray method or the geometric vector flux approach [21–34]), while others are based on more accurate and flexible ray-tracing technologies [9,35]. Simplified methods have advantages of high computational speed and low cost, but the disadvantages are lack of control over assumptions, limited selections of system configurations and limited flexibility for design optimizations. If the system studied is significantly non-standard, a tailored computer simulation may be required to achieve accurate results [36]. The ray-tracing technologies usually offer such detailed modeling capabilities. Over the years, the Monte Carlo ray-tracing (MCRT) method has been proven to be a more efficient numerical method to simulate the optical characteristics and performance of solar collectors [37–51], accurately taking into account various realistic optical effects respectively or simultaneously, such as the realistic sun-shape profile, the incident angle and surfaces geometry dependent optical properties, the wavelength-dependent optical properties, the non-orthogonal incidence, the tracking error, the imperfect mirror surface, the deformation of the parabolic profile, the shadow and end effects, the light extinction in the media and the defocalisation of the receiver, etc. [6]. Many significant numerical PTC optical models based on this method have been developed in recent years, which have been thoroughly tested or experimentally validated [6,48,49].

At the same time, there are also many optimization analyses to improve the optical performance of PTCs. They are carried out by combing these modeling methods of PTCs and the design or optimization techniques mentioned above. Rabl et al. [26] optimized the design of PTCs with a simple hand calculator using a