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CRS4-2: A numerical code for the calculation of the solar power collected in a central receiver system

Erminia Leonardi*, Bruno D'Aguanno

CRS4, Center for Advanced Studies, Research and Development in Sardinia, Parco Scientifico e Tecnologico, POLARIS, Edificio 1, 09010 PULA, CA, Italy

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ABSTRACT

The analysis of the solar power collected at the receiver in solar tower systems requires the use of efficient and accurate numerical codes. This paper presents a new Fortran computer program, CRS4-2 (an acronym for Crs4 Research Software for Central Receiver Solar System SimulationS), for the simulation of the optical performance of a central receiver solar plant. The implemented mathematical algorithm allows for the calculation of cosine, shading and blocking effects for heliostats arbitrarily arranged in the solar field. Special attention has been given to ensure the maximum flexibility concerning the number, dimension, shape, and position of the heliostats. In the present implementation, the solar field can be composed of both square and circular heliostats possibly mixed together, each one of them characterized by the size and height from the ground. The modular design of CRS4-2 allows the extension to heliostats of arbitrary shape with only minor modifications of the code. Shading and blocking effects are computed by a tessellation of the heliostats: therefore, the numerical accuracy depends only on the refinement of the tessellation. The application to actual systems has shown that the approach is stable and general.

1. Introduction

The solar field of a central receiver system (CRS) is made up of several hundreds (or even thousands) of mirrors, called heliostats, placed around a receiver, which, in its turn, is at the top of a central tower. As reported by M. Sanchez and M. Romero [1], a CRS of 30 MWth located at the Seville latitude requires 593 heliostats, with an individual reflecting surface of 64 m^2. In recent CRS applications, the number of heliostats is growing while their surface is shrinking. An example is given by the application illustrated by S. Schell [2] in which there are 12,180 heliostats, each having a surface of ≈ 1.14 m^2.

For each heliostat, a computer controls the rotation around two axes to guarantee a continuous correct orientation, with a tracking error of less than a fraction of a degree. This ensures that the reflected sunlight focuses directly on the tower receiver, where an absorber is heated up to temperatures of about 1000 $^{\circ}$C, or more, by the concentrated sunlight. Air (or another heat transfer fluid, HTF) transfers the absorbed energy to a heat exchanger coupled to a gas or steam turbine, in its turn connected to an electrical generator.

The positioning of the mirrors around the tower is a key point and it depends on many factors. Indeed, the system suffers losses caused by the cosine effect, shading and blocking by neighboring heliostats, and, therefore, the amount of energy collected at the receiver, for a given position of the sun, is a function of the position and form of the heliostats, and of the receiver height.

An extended list of quantities which controls the value of the thermal power transferred to the HTF is given in Table 1 of the paper of F. J. Collado [3] and they have been established from a CRS performance test by J.E. Pacheco et al. [4]. These quantities can be classified as geometrical, material and energetical. Among them, the effect of the geometrical quantities can be computed without any other approximations apart from those defining the numerical algorithm, while the estimation of the effect of the other quantities involve the definition of a model for the evaluation of the thermal energy collected in the central receiver, and therefore they can be a source of approximations and errors.

The main aim of this work is to show that (i) the effect of all geometrical quantities can be summarized in a unique function, here introduced for the first time and termed "characteristic function" of the CRS solar field, and (ii) that this characteristic function can be evaluated effectively with a small and under control numerical error.

For a given solar field, the characteristic function is defined, for a given position of the sun, as the effective surface (or fraction) of

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* Corresponding author. Tel.: +39 0 709250328; fax: +39 0 709250216.
E-mail address: ermy@crs4.it (E. Leonardi).

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the heliostats which reflects the sun rays to the receiver. The characteristic function can be written as $A_{\text{eff}}(t) = A_h - A^*_{\cos}(t) - A_{\text{sb}}(t)$ (or as $\eta_{\text{eff}}(t) = 1 - \eta^*_{\cos}(t) - \eta_{\text{sb}}(t)$) in which the terms on the right are the total heliostat's surface (A_h), the reduction of this surface due to the cosine effect ($A^*_{\cos}(t)$), and to the shading and blocking effects $A_{sb}(t)$. Following P. Schramek and D.R. Mills [5], one can define two geometrical efficiencies related to the ground's area and the heliostat's area, respectively, $g_g(t) = A_{\text{eff}}(t)/(A_g \cos|\vec{n}\cdot\vec{s}(t)|)$ and $g_h(t) = A_{\text{eff}}(t)/A_{\cos}(t)$, where A_g is the ground area, $\vec{n}$ is the versor normal to the ground and $\vec{s}(t)$ is the versor of the solar beam. These geometrical efficiencies are a good estimation of the actual efficiencies, in which the material and energetical quantities (depending on the chosen materials and site latitudes) are also taken into account, and a good starting point for their determination.

Commercial codes are available for the study of the solar field performances, but most of them have been developed in the late 70s and successively improved, especially integrating them with the possibility of economical analysis. An interesting and exhaustive review of the most used codes has been presented by Garcia *et al.* [6].

In Ref. [6], the available codes are divided into two categories, depending on the underlying mathematical algorithm. The first category collects the codes based on Monte Carlo ray-tracing methods for the calculation of the shading on the heliostats. These statistical methods consist in choosing randomly a bundle of rays which come from a surface 1 toward a surface 2, with an irradiance on the surface proportional to the number of impacting rays. The algorithm, which is applied twice, first from the sun to the heliostat surface, and then from the heliostat surface to the receiver, implies large computational effort in order to achieve satisfactory results. The codes MIRVAL [7] and SolTRACE [8], for example, belong to this category.

A second type of codes uses mathematical algorithms based on convolution methods, for which reflected rays from elementary mirrors are considered with error cones calculated by convolutions of normal Gaussian distributions corresponding to each error. The codes UHC [9,10], DELSOL [11] and HFLCAL [12], for example, make use of this algorithm.

However, and as already pointed out in other research papers [6,13], many of these codes are rather complex in particular for the handling of solar field of heliostats, while the majority of them contains, since the beginning, the assumption a well defined viewpoint (i.e. the optimization of heliostat usage and not of ground consumption, the use of just flat land, etc.). In addition, when they are used in their full glory (CRS optimization), they also require long computational time. For all these reasons, the research of approximate and semi-analytic expressions able to evaluate, in an easy and fast way, the CRS efficiencies [3,13] remains as an active research field.

This situation has motivated the development of the model proposed in the present research work and its implementation into an efficient computational code. The mathematical model is here described in details with the aim to give to all interested readers the possibility to develop their own code, and to test and validate the obtained results against well defined and documented cases.

The mathematical model implemented in CRS4-2 represents an alternative to the existing models cited above. The shadows on each heliostat are calculated by considering the effective path of the sun rays, namely, the various intersections of incident and reflected sun rays with the plane of the heliostats. The calculation of the effective surface reflecting the sun rays is achieved by a tessellation of the surface of the heliostat, which allows a numerical integration of the shaded area, with a level of approximation controlled by the number of tesserae (or better by their area) forming the surface of the heliostat. The heliostats can be flat or concave and the beam quality of the reflectors is also taken into consideration. Indeed, sunshape, curvature and waviness errors of the reflecting surface, as well as possible tracking errors in the drive mechanism are taken into account in the mathematical model. CRS4-2 allows the study of solar fields located on non-flat grounds, of heliostat fields with maximum ground coverage, of the typical heliostat field configurations for Beam-Down [14] and Multiple-Apertures [15] CRS, and, finally, of multitower configurations. The detailed description of some of these possibilities is outside the scope of the present work and they will be presented in forthcoming works.

The remainder of the paper is organized as follows: the next section reports the mathematical algorithm for the calculation of the solar energy collected by the solar field for a CRS; in Section 3 some applications of the model are presented, together with an analysis of the numerical stability and computational resources of the developed code; finally, a conclusion section presents some conclusive remarks.

2. Mathematical model

The solar field here considered is composed of N_h heliostats located arbitrarily around the tower. Each heliostat is characterized by its shape, square or circular (therefore, by its side, $l_{h,}$ or radius, $r_{h,}$ respectively), by its eccentricity, and by its height from the ground (indicated by the height of the "fixed" point, or center, of the mirror). These data are read by the code from an external file, where, for each heliostat, one must indicate the cartesian coordinates of its center, a flag to distinguish between square or circular heliostat, the corresponding value of l_h or $r_{h,}$ and its eccentricity. Therefore, it is possible to consider solar fields composed of mixed square and circular heliostats of different size and height from the ground, which is assumed flat and in the *xy* plane: the choice of heliostats of different height from the ground has been motivated by the need to describe also grounds characterized by a non planar slope.

The mathematical model contains some approximations. First of all, the shadow produced from the tower on the solar field has been neglected. This is motivated by the fact that the aim of the present paper is to emphasize an interesting aspect in the design of a solar tower system: it is useful to introduce a sort of hierarchical procedure, whose first step is focused on the determination of the characteristics of the solar field, with the tower simply assimilated to an aim point at a given height from the ground.

Therefore, no attention is dedicated to the geometrical characteristics of the receiver, which is simply seen as a surface which fully absorbs the sunlight reflected by the lighted portions of the heliostats. Moreover, the field power losses due to atmospheric attenuation and reflectance are also neglected. The introduction of these effects into the model is trivial, but not relevant to the aim of the present work, because they are related only to the actual atmospheric conditions and to the material characteristics of the heliostats, and are not related to the relative disposal of the heliostats in the solar field.

In the chosen coordinate system (referred to in the following as "tower system of coordinates"), East is in the *x* positive direction and North is in the positive *y* direction, as shown in Fig. 1, where also the zenith and azimuth angles defining the sun position are indicated. The solar tower is located at the origin of the axes, with the receiver at a height $h_{r.}$ In Fig. 1 α_z and ϕ are the zenith and azimuth angles, respectively. In particular, α_z is the angle that the sun ray forms with the normal to the ground and ϕ is the angle that the projection of the sun ray on the *xy* plane forms with the South direction. In the following a different system of coordinates is also used: it depends on a given heliostat *k* (it is indicated hereafter with