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Technical note

# Mirrors array for a solar furnace: Optical analysis and simulation results

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ABSTRACT

The optical design of a concentration system for a solar furnace is studied, proposing several possible solutions. The foreseen use of this solar furnace is to test components and methodologies for solar applications. The analysis assesses and compares the optical performances of several possible configurations. The possibility of employing in a solar furnace an array of off-axis mirrors as primary optics is examined comparing simulations with various diameters and different configurations. In particular the paper compares spherical mirrors, parabolic mirrors with axis inclined with respect to the heliostat rays and a paraboloid with axis parallel to the rays arriving from the heliostat. It proposes an optimal solution, with spherical mirrors on a spherical envelope, which is compared to the heliostat-axis paraboloid. Considering realisation tolerances, mirrors positioning, mirrors pointing and solar divergence effects they equivalently concentrate the sunlight on the receiver.



## 1. Introduction

In the last fifty years several solar furnaces have been studied, designed and realised, both for research applications and for materials test [1–7]. A solar furnace is a structure that uses a concentrated solar beam to produce high temperatures, usually for sample test. These plants require a captation area inferior to that used in electricity production plants, but the mirrors system should generate a higher power density to improve usage flexibility. The optical layout of this plant type is characterised by a heliostat (composed of flat or curve mirrors), a possible primary optics to concentrate the light (if not focused by the heliostat) and a solar receiver (sometimes with an extra concentrator before the receiver entrance). The mirrors field is realised by means of one or more matrices of tens or hundreds elements, placed on the ground and orienting the reflected flux towards a receiver on a tower [8]. Heliostat fields in central tower power applications are huge primarily because high amounts of radiative energy have to be collected; vast plants show a spot enlargement due to the solar divergence but the large plant size reduces mutual mirrors shadowing effects [9,10]. The receiver often is located at several tens of meters, complicating the access and thus needing further structures. The use of few large size heliostats with fixed parabolic secondary is possible: it was realised for example at Odeillo, in France [11], but it needs huge funds and a specific soil preparation. Please note that, from an optical point of view, the best way to concentrate collimated rays from a source at infinite distance (the sun) is to utilise a parabolic mirror (or a part of it) with the axis parallel to the rays direction (parallel-axis paraboloid), so to eliminate the spherical aberration and minimise coma and astigmatism. It is very difficult to practically produce this system, but in Section 3 the parallel-axis paraboloid will represent a reference (reference solution) in order to evaluate the behaviour of the finally chosen solution.

Due to the difficulties to realise a very large single mirror or few large mirrors as in the Odeillo plant, the standard solution for the concentration stage is an array of mirrors (“facets”) of small sizes with respect to the total system [12–14]. Several studies examined how to realise and mount the single mirrors [15]: often they foresee to use as “facets” various sets of spherical mirrors in a parallel-axis system configuration (with the axis of the theoretic surface “sustaining” the mirrors parallel to the solar rays direction) [7,16,17].

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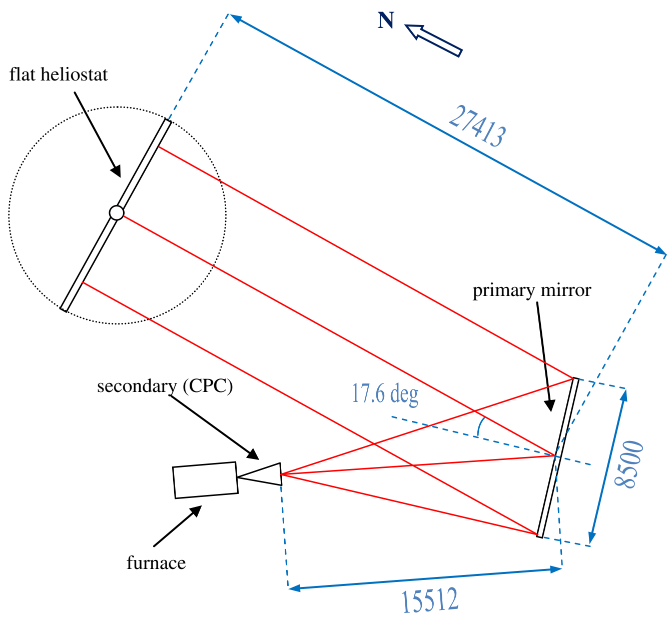


**Fig. 1.** Scheme of the ENEA plant (lengths in mm); in the figure, the flat heliostat is oriented at noon, then the rays that hit the heliostat come from South (in the same vertical planes of rays from the heliostat to the primary mirror).

Indeed for the DLR furnace at Cologne (Germany) another solution was chosen: a spherical mirrors array mounted on a flat layout inclined with respect to the direction of rays from the heliostat (inclined-axis setup) [18]. In this case and in the paper of D. Riveros-Rosas et al. [7], the mirrors have three different focal lengths to increase the sun concentration. However, in order to contain the costs the task should be to apply a set of identical mirrors, determining the best theoretical surface “sustaining” the mirrors set. With this aim, power distribution on the target and beam quality (Seidel aberrations) were analysed, comparing various configurations.

The furnace is under realisation near Naples (Italy), in a site of the ENEA-Portici research centre, with 40°49′11″64 N of latitude, at sea level. Fig. 1 summarises the installation scheme.

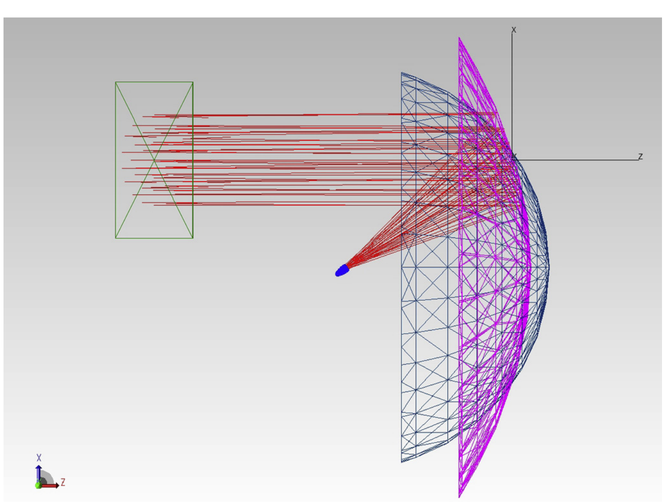

**Fig. 2.** Heliostat (green line), mirror envelopes (blue spherical, purple parabolic), target (CPC, light blue) and rays from the sun (direction of rays corresponding to Jun, 21 at noon, Portici, Naples, Italy) reflected from heliostat and from the parabolic envelope, that corresponds to the “reference solution”. The simulated sun is not visible.

The heliostat is a composite flat mirror, with sizes 10 m × 12 m ($H \times L$), and the primary optics must be centred at a distance 27.413 m from the heliostat centre. It is an off-axis concentrator because there is an angular misalignment of 17.6° between the normal of the primary centre and the primary-heliostat connection: in particular in the horizontal plane this angle is 16.5°, while in the vertical plane is 7.5°.

The Compound Parabolic Concentrator, employed as secondary optics, is located at 15.512 m from the primary optics centre. The furnace entrance aperture (the CPC output window) should measure 230 mm in diameter, so the CPC input window, for the maximum input beam inclination (30.3°), will have a diameter of 603.6 mm. The fundamental request is to obtain at least 30 kW of maximum flux at the receiver entrance. Due to the furnace scope, there are no requirements about specific profiles of irradiation at the furnace entrance.

## 2. Shape and performances of primary optics mirrors

### 2.1. Research methodology

A preliminary evaluation, at least rough, of the beam angular distribution is necessary. It essentially depends on solar divergence, heliostat pointing errors and mirrors surface features (slope errors and diffused reflectance) [19]. The primary pointing errors are neglected, assuming that during the system erection phase every spherical mirror gets actually aligned correctly to point towards the target centre. The considered contributions have various angular dependences: the solar divergence has its peculiar form, which for the purposes can be approximated as a uniform distribution with semi-aperture 4.7 mrad [20]; the heliostat pointing errors are almost uniform in time, with a semi-angle depending on the tracking system characteristics, of about 3 mrad [19]. The assessment of mirrors local slope errors is more complex: supposing a Gaussian distribution, with standard deviation $\sigma = 5$ mrad [21], and converting it [22] into a uniform distribution with semi-aperture $a = \sqrt{3} \cdot \sigma$, it can be obtained an acceptable good approximation of the real behaviour [23].

Hence the study includes two simulations with different angular profiles:

- uniform distribution with semi-aperture 4.7 mrad (approximate solar distribution);
- Gaussian distribution with $\sigma = 5.9$ mrad (reporting uniform distributions to Gaussian and considering that the convolution variance is the variances sum).

It is evidently impossible to construct a single mirror as primary optics, or a multi-mirror parabolic surface, for costs reasons. So the simplest solution is to realise a set of identical mirrors that allow to obtain an acceptable power concentration at furnace entrance. Hence the task is to design and place an identical mirrors set, arranged to intercept the radiation arriving from the heliostat and to redirect it towards the furnace with the maximum possible efficiency.

Concerning shape and size of the mirrors, literature [15] and practical estimations suggested to use hexagonal mirrors with 1 m of vertex–vertex distance. For validation, the simulations considered mirror diameters between 0.5 m and 2 m. Due to the severe environmental conditions (seaside site), rear-face aluminated mirrors were preferred, because their glass absorption losses are acceptable (under 0.1–0.5% between 400 and 1500 nm of wavelength for few mm thickness), while the reflection on the mirror first surface is anyway directed to the target, without appreciable differences from the principal reflection (both for the reasonable