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Evaluation and assessment of gravity load on mirror shape and focusing quality of parabolic trough solar mirrors using finite-element analysis

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HIGHLIGHTS

- Finite element models of EuroTrough type collector support structure developed.
- Type and stiffness of support structure influences mirror shape accuracy.
- Rms mirror shape values differ even more in non-zenith collector orientation.

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ABSTRACT

In order to achieve high optical efficiency of solar parabolic trough collectors and high performance of the solar field, the concentrator mirrors in concentrating solar power plants are expected to maintain accurate parabolic shape over the daily operation cycles. In addition to shape imperfections introduced by the manufacturing process, deformation due to gravity load and mounting forces is an inevitable factor affecting shape accuracy in all types of parabolic trough collectors.

In this paper the effect of gravity load on mirror shape and resulting slope and focus deviation values is characterized and quantified in finite element analyses referenced to specific lab tests. Inner and outer ideally shaped parabolic mirror of RP3 geometry are evaluated for various discrete collector angles relevant for operation on different collector support structures. Three finite-element-models are included in the study: two with idealized support structures (ideal and elastic case) and one including the cantilever arms as relevant parts of the EuroTrough type collector support structure (cantilever case).

Constructional design and stiffness of the support structure significantly determine characteristic and magnitude of deformation. Resulting rms values of the sagged mirror panels are as high as $SDx = 1.7$ mrad and $FDx = 6.3$ mm (inner mirror, elastic case) and $SDx = 1.1$ mrad and $FDx = 5.6$ mm (outer mirror, cantilever case). Depending on the type of support structure, minimum and maximum values occur at different collector angles. Rms slope and focus deviation values are closer to the 0° (zenith) collector angle case than to the non-deformed (ideal) mirror shape. This leads to optimizing the mirror shape for 0° (zenith) collector angle. Different support structures in design and stiffness for shape accuracy assessment in laboratory and those used in the collector make it difficult to find one optimum shape for all types of mirror and collector.

1. Introduction

Concentrating solar collectors are used in solar thermal power plants (also: concentrating solar power plants, CSP) to focus solar beam irradiation, bring the heat transfer medium to temperatures of typically 390 °C and drive a conventional steam cycle with generator for power generation at scales of 30–300 MW of electric power. The concentrating solar collectors require good shape of the reflector panels during operation while the concentrator is continuously tracking the sun position. Deviations from the ideal shape are on the one hand induced by the mirror manufacturing process and on the other hand by inevitable factors in operation such as deformation due to dead load, inaccurate mounting of mirrors to a possibly imperfect collector structure or wind loads. The mirror shape of any kind of concentrator type (parabolic trough, linear Fresnel, heliostat, or dish) is measured in laboratory, in the production line, or in the field by well-established measurement methods such as Video Scanning Hartmann Optical Test (VSHOT) [1], visual inspection systems [2,3], and the widely spread fringe reflection or

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deflectometry techniques [4–6]. For studying the effect of loads and mounting forces it is convenient to employ finite element analyses techniques [7]. The modeling approach allows determining the impact of individual influence factors on shape deviation and resulting parameters, as well as analysis of the impact of a combination of two or more factors.

As presented by Geyer et al. the development of the EuroTrough collector was advanced by FE-analyses [8]: Structural investigation under different load cases were carried out and the optimal configuration was identified. Christian and Ho [9] performed a finite element deformation analysis for a LS-2 parabolic trough collector in two representative positions, zenith collector angle and collector facing horizon. Resulting absolute slope deviation values were as high as 2 mrad for mirrors exposed to gravity load and as high as 3 mrad for a change from one collector angle to the other. In a later study, the impact on the intercept factor is determined [10]. Lüpfert and Ulmer [11] introduce a further shape quality parameter named "focus deviation" and demonstrate that this parameter is closely related to the energy efficiency (measured as intercept factor) of a parabolic trough collector.

Moya and Ho created Finite Element Models of the heliostats at the National Solar Thermal Test Facility at Sandia National Laboratories in Albuquerque [12]. The effect of displacements under different load scenarios was investigated and compared to experimental results. A later study by Yuan, Christian, and Ho involved the Advanced Thermal Systems (ATS) heliostat [13]. Another study by Biggio et al. published 2013 deals with linking FEA with ray tracing software in form of a Finite Element Ray Tracer (FERT) [14]. The advantages of an all-in-one workflow for the design process of new collector generations are pointed out. Gong et al. performed dynamic measurements at heliostats in order to identify modal parameters and characterize the influence of windloads [15]. The results allow an optimization of the heliostat design for different operational conditions. Cheng et al. connected the Finite Volume Method (FVM) with Monte Carlo Ray Tracing (MCRT). The effect of geometric parameters of the parabolic trough system under investigation on the focus-shape was analyzed theoretically and eventually compared to the numerical FVM-MCRT-results obtained in simulations [16].

Previous analyses for parabolic trough solar collectors employing RP3 mirror geometry focused on determination of gravity-induced deformation [17]. The resulting slope deviation in three selected collector angles and one typical laboratory measurement position for two idealized collector model cases (an ideal case with ideally rigid collector support structure and an elastic case with ideally rigid structure using the elastic connections employed in EuroTrough type collectors to attach the mirrors) was determined. The main findings include that slope deviation compared to ideal shape and compared to zenith collector angle are in the magnitude of shape quality itself and that the support structure determines deformation characteristic and magnitude of displacement and resulting slope deviation. For all evaluated angles deformation and thus slope deviation is more pronounced for the elastic case.

This paper extends the analyses on parabolic trough solar collectors to the whole angular range in operation, introduces a third model case which includes relevant parts of a EuroTrough type collector support structure, and assesses the impact of gravity-induced deformation in terms of slope and focus deviation parameters. In order to characterize and quantify the effect of gravity load on mirror shape, slope and focus deviation, the deformed mirror in each evaluated angle is compared to the non-deformed mirror shape, and to the shape in zenith collector angle. The purpose of the studies is to understand the effects of supporting geometry, mounting elements and panel properties on the collector performance and possibly derive improved specifications.

2. Methodology

2.1. Definitions and geometry

In EuroTrough type concentrators or similar designs with RP3 mirror geometry the parabolic collector shape of 5776 mm width is formed by two inner (1700 × 1641 mm) and two outer mirror panels (1700 × 1501 mm) as reflectors of a cylinder-parabolic collector. The receiver tube is located at a distance of 1710 mm (focal length) from the vertex. The mirror panels are bent and coated 4 mm float glass sheets with four ceramic pads each glued to the mirror back side for mounting to the metallic collector support structure.

By definition [18], the origin of the collector coordinate system is located in the parabola vertex. The *y*-axis is oriented parallel to the parabola symmetry axis, pointing in northern direction. The *z*-axis points from the parabola vertex towards the focal line. The *x*-axis corresponds to mirror curvature direction and is oriented in order to have a right-handed coordinate system, see Fig. 1.

2.2. Parameters for the assessment of mirror shape accuracy

In concentrating solar power applications mirror shape accuracy is evaluated in terms of surface slope deviation which is defined as the angle between actual and ideal surface normal vector. An outward rotation of the deformed surface normal vector (pointing to the outer edges of the parabolic trough) is defined as positive slope deviation, an inward rotation (pointing to the center of the trough) as negative slope deviation. A statistical parameter characterizing the shape accuracy of the whole mirror surface is the root mean square (rms) value of local slope deviations, SDx:

$$SDx = \sqrt{\sum_{i,j=1}^{n} \left(sdx_{ij}^2 \cdot \frac{a_{ij}}{A_{\text{tot}}} \right)} \tag{1}$$

with local slope deviation values sdx_{ij}, the according surface element areas a_{ij} projected into the aperture plane and the total aperture area A_{tot}.

The maximum allowable value of slope deviation depends on the distance of the reflecting surface element to the focal line and the geometry of the receiver. The deviation of the reflected light beam from the ideal focal line, so called local focus deviation, was introduced as a further parameter characterizing mirror shape accuracy [11] It is derived from local slope deviation and the distance d of the according reflecting surface element to the ideal focal line, e.g. in x-direction:

$$fdx_{ij} = (2 \cdot sdx_{ij}) \cdot d \tag{2}$$

The factor 2 results from the law of reflection. According to Eq. (1) a root mean square focus deviation FDx can be calculated based on local values.

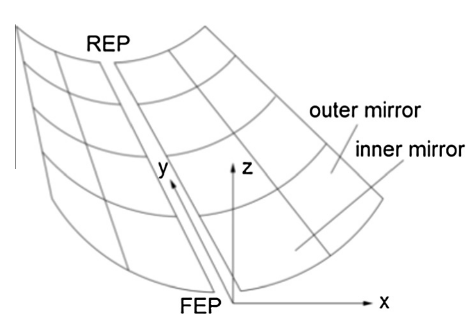

Fig. 1. Coordinate system of a parabolic trough collector module (FEP/REP = Front/Rear End Plate).

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