Absorber tube displacement in parabolic trough collectors – A review and presentation of an airborne measurement approach

C. Prahl a,⁎, M. Röger a, B. Stanicki b, C. Hilgert a

a Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR), Institute of Solar Research, Ctra. de Senes s/n, 04200 Tabernas, Spain
b Hochschule Ravensburg-Weingarten, 88241 Weingarten, Germany

⁎ Corresponding author.
E-mail address: christoph.prahl@dlr.de (C. Prahl).

1. Introduction

The terms Concentrating Solar Power (CSP) or Solar Thermal Energy (STE) cover all methods where solar radiation is concentrated by lens- or mirror arrays before harnessing the thermal energy of the sun light. Among the different systems which are commercially available (IRENA, 2013), the Parabolic Trough Collector (PTC) is considered the most mature technology with 4.2 Gigawatt (GW) installed capacity worldwide (CSP-Today, 2017). PTCs (Price et al., 2002; Fernandez-Garcia et al., 2010) are high precision optical devices, and the optical and mechanical properties of the concentrator and the Receiver tube (aka.: Heat Collecting Element (HCE)) are crucial for the efficiency of the power plant.

The optical performance depends to a large extend on the geometric accuracy of the concentrator. This share is commonly described by the Intercept Factor (γ), which is the ratio of irradiation hitting the absorber and reflected irradiation from the concentrator following the definition of Bendt et al. (1979, p. 9). Three independent geometrical properties determining the γ can be distinguished (Bendt et al., 1979; Pottler et al., 2014).

1. The shape accuracy of the mirror surface is commonly represented by slope deviations of the mirror from the design shape (Slope deviation in curvature direction (SDc) and Slope deviation in longitudinal direction (SDL)). Mirror shape accuracy is considered to be the most important property for any CSP concentrator. It depends on the compliance with tolerances of the concentrator components (e.g. mirrors and structure), on the assembly accuracy and the concentrator’s capabilities to withstand gravitational loads. A state of the art review on methods to determine the shape and/or slope deviations of CSP concentrators is presented in Ren (2014).

2. Tracking accuracy describes the deviation between the optical axis of the concentrator and the sun position, projected on the XZ plane of the concentrator (Bendt et al., 1979, Sec. 2.1, Fig. 2.1). Assuming a correct operation of the tracking system (mechanics, sun position algorithm, and optional sun-sensors), the local direction of the optical axis along the trough may be altered by wind, static unbalance and bearing friction. Such torsion effects are best assessed by means of inclinometers (Pottler et al., 2014).

3. This paper focuses on Absorber tube displacement along the optical axis (ΔZAbs) and Absorber tube displacement in lateral direction (ΔXAbs). In all operation conditions, the absorber tube center line is supposed to be co-axial with the PTCs focal line.

There are several ways to estimate the impact of geometrical deviations on the γ. The statistical Ray Tracing (RT) approach presented in Bendt et al. (1979) consist of folding the sunshape with additional statistical concentrator errors, that way generating an...
**Nomenclature**

**Abbreviations**
- CSP: Concentrating Solar Power
- CSR: Circumsolar Ratio (Buie and Monger, 2004)
- DLR: Deutsches Zentrum für Luft- und Raumfahrt e.V.
- DNI: Direct Normal Irradiance [W/m²]
- DSG: Direct Steam Generation
- EOR: Exterior Orientation: camera positions obtained by photogrammetric evaluation (Luhmann et al., 2006)
- ET: EuroTrough Collector (Geyer et al., 2002)
- FEP: Front End Plate: end face of Parabolic Trough Collector (PTC) steel structure orientated towards the drive pylon
- GUI: Graphical User Interface
- GW: Gigawatt
- HCE: Receiver tube (aka: Heat Collecting Element)
- HTF: Heat Transfer Fluid: see (Vignaroban et al., 2015)
- IOR: Interior Orientation: Set of parameters describing the internal geometry and lens distortion of the camera (Luhmann et al., 2006)
- KONTAS: Concentrator Test Bench at PSA, Almeria, Spain
- LOS: Line-of-Sight
- MATLAB: MAtlas LABoratory: proprietary programming language developed by MathWorks
- NREL: National Renewable Energy Laboratory
- PG: Close Range Photogrammetry
- POI: Point of Interest
- PSA: Plataforma Solar de Almería, Spain
- PTC: Parabolic Trough Collector
- PV: Photovoltaics
- QFly: Airborne Qualification of CSP Plants
- REP: Rear End Plate
- REPA: Rotation and Expansion Performing Assembly: flexible tube connector or ball joint to link HCE with solar field header
- ROI: Region of Interest
- RP3: PTC Mirror quasi standard with 1710 mm focal length and 5774 mm aperture width
- RT: Ray Tracing
- SCA: Solar Collector Assembly
- SCE: Solar Collector Element
- SPRAY: Solar Power RAYtracing Tool (Buck, 2010)
- STE: Solar Thermal Energy (same as CSP)
- STRAL: Solar Tower RAY tracing Laboratory (Belhomme et al., 2009)
- TARMES: Trough Absorber Reflection MEasurement System
- UAV: Unmanned Aerial Vehicle
- WP: Waypoint of UAV flight route

**Mathematical symbols and units**
- \( f \): focal length
- \( \Delta X_{abs} \): absorber tube displacement in lateral direction
- \( \Delta Z_{abs} \): absorber tube displacement along the optical axis
- \( \gamma \): intercept factor: ratio of solar irradiation hitting the receiver versus irradiation reflected from the concentrator, when \( \rho_{ref}, \tau_{class}, \) and \( \tau_{sec} \) were equal to 1 (Bendt et al., 1979)
- \( SD_X \): slope deviation in curvature direction
- \( SD_Y \): slope deviation in longitudinal direction
- \( T_{HTF} \): Heat Transfer Fluid (HTF) temperature
- \( \theta \): PTC tracking angle: 90° corresponds to zenith
- \( \rho_{ref} \): specular mirror reflectivity
- \( \tau_{class} \): glass envelope tube transmissivity
- \( \tau_{sec} \): absorber tube absorptivity

1 Bellow protections and receivers supports.

“effective” source with a wider angle distribution compared to the initial sunshape. Applications of statistical RT to PTC fields are presented among others in Lüpfert et al. (2007) and Pottler et al. (2014). A brief explanation on advantages and drawbacks of this method can be found in Zhu and Lewandowski (2012, Sec. 2.2.2).

An extensive analytical approach to determine the flux incident on an absorber tube considering statistical concentrator errors and a bent tube is presented in Khanna et al. (2013, 2014, 2015). An analytical approach called FirstOPTIC, which preserves the spatial information of shape- and absorber tube deviations while employing a probability approximation from Bendt et al. (1979) for the sun-shape was developed by Zhu and Lewandowski, 2012 and Binotti et al. (2012).

Numerical RT is the state of the art approach to assess the optical performance of CSP systems. Based on measured concentrator geometry, RT predicts the optical performance correctly even for cases where systematic deviations are present. RT simulations consider blocking and shading elements\(^1\) which interfere with incident and reflected radiation. A current review on available RT tools and their abilities is available in Ho (2008) and Bode and Gauche (2012).

Absorber tube displacement may effect both the optical performance of the concentrator as well as the result of optical measurement techniques using the absorber tube position as an input parameter. This article was motivated by the development of Airborne Qualification of CSP Plants (QFly) (Prah et al., 2011, 2013; Stanicki, 2011), where slope deviations of PTC solar fields are characterized by the Trough Absorber Reflection MEasurement System (TARMES) (Ulmer et al., 2009) approach, which in turn is based on the distant observer technique proposed by Wood (1981). For this approach, the absorber tube serves as a pattern. The absorber reflection visible in the mirror is used to deduce the mirror shape. Therefore it was necessary to develop a method suited to simultaneously measuring the absorber tube position along with mirror shape deviations. In addition, a reasonable statement on the optical performance by means of RT is only possible if the entire geometry is known with sufficient spatial resolution and accuracy.

Section 2 of this article describes the cause and effect of absorber tube displacement as well as applications of absorber position data. In Section 3, an overview on state-of-the-art methods to measure the absorber tube deviations is given. In Section 4, a new airborne approach for absorber tube positioning suited for large number of collectors is introduced and validated against a high-precision photogrammetric benchmark measurement. The results and further suggestions are discussed in Section 5.

2. Absorber tube displacement

The thermal energy absorbed by the HCE is transferred to a Heat Transfer Fluid (HTF) circulated inside the stainless steel tube with typical diameter in the range of 70–90 mm (Schott, 2015b,a). All HCEs designed for high temperature applications are surrounded by an evacuated glass envelope tube with an anti-reflective coating to minimize convection heat losses and to maximize the transmittance. A spectral selective coating of the steel tube assures high absorptivity an low radiative heat losses. The cost share of the HCEs is about 7% of the total investment cost of the entire plant.
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