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Aerodynamics of new solar parametric troughs: Two dimensional and three dimensional single module numerical analysis

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ABSTRACT

Two new symmetric Non Imaging Parametric Trough Collectors (PmTC) with circular and flat evacuated receivers have been recently proposed with a potential improvement in the net concentration ratio relative to the thermodynamic ideal limit beyond 65% compared to commercial Parabolic Trough Collectors (PTC) while maintaining or increasing the rim angle. Both collectors are composed of a symmetrical parametric primary discontinuous reflector geometry and a secondary concentrator with potential to reduce the wind loads and effectively reduce the cost of the solar field. Computational Fluid Dynamics (CFD) has been used as "virtual" wind tunnel to compare the flow around a single model-scale module of the two PmTCs and the two commercial LS2 and LS3 PTCs, in a range of pitch angles. Two case studies - 2D and 3D simulations - have been analyzed. Wind turbulence intensity was not taken into account, as the aim is to compare qualitatively the aerodynamic behavior of the different collectors. Velocity vector fields, mean values of aerodynamic drag, lift and moment coefficients and flow patterns were computed. Results confirm that the PmTC with circular receiver behaves very similarly to the LS2 and LS3 geometries for the drag, lift and moment coefficients. The PmTC with flat absorber shows the worst performance showing more than 25% penalization in terms of maximum drag and moment values in comparison with the other three collectors. The 2D case study shows worse coefficients when compared to the 3D case by a factor of 2. Analyses of averaged velocity vector fields at mid-section show a smaller wake in the 3D case study for the four collectors and all pitch angles and a lower influence of the gap in the primary reflector. An additional comparison of the LS2 3D results with and without turbulence intensities - the latter results taken from an earlier work - shows very good agreement both for the mean lift and moment values and a 20% difference for the mean drag due to the fact that turbulence fluctuations over the mean velocity profile add more energy to the system. Further 3D CFD simulations with turbulence intensities for a complete solar field design are needed in order to evaluate the potential of both PmTC to effectively reduce the cost of the solar field. This work has permitted to advance in the understanding of the potential of non-imaging optics to generate new geometries able to improve thermosolar technology from an aerodynamic point of view.

1. Introduction

Current PTC technology is the most proven and lowest-cost large scale solar thermal concentrated power technology. The first Solar Electric Generating Systems (SEGS) plants were built in the Mojave Desert in California in the 1980s using the LS-2 and LS-3 generations of PTCs and marked the beginning of the modern development of Concentrated Solar Power (CSP) plants worldwide. Today most of the commercial trough plants make use of the LS3/Eurotrough parabolic optics also with evacuated receiver tubes with glass envelope (Fernández-García et al., 2010).

The PTC solar field is designed taking into account the following operational conditions (Giannuzzi et al., 2007):

- Response under normal operational conditions with low and medium winds maintaining an acceptable optical efficiency.
- Transition between normal operating conditions and survival positions under medium-to-strong or strong winds. The survival must be ensured in any position under medium–strong winds so that the drive must be able to take the collector to safe positions.
- Survival under strong winds in stow position.

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and design requirements:

- Safety. The collector structures exposed to its loads must guarantee adequate safety levels to ensure public protection.
- Optical performance. The structure must guarantee a suitable stiffness in order to obtain, under operational conditions, limited displacements and rotations.
- Mechanical functionality. The structural adaptation to loads must not produce interference among mobile and fixed parts of the structure.
- Low cost.

A significant factor influencing the economic viability of PTCs, both in terms of operational and design requirements, is the magnitude of the wind loads and the resulting structural requirements. Moreover, the shape of the collector, its height above the ground, the collector pitch angle, the number and arrangement of collectors in an array and the wind direction are parameters that can modify the loads affecting the collector (Peterka et al., 1980).

From the LS3/Eurotrough geometry two well-differentiated R&D strategies are currently undertaken to reduce its cost and gain competitiveness:

(i) developing larger parabolic through collectors which implies a higher demand in tracking accuracy and lower tolerances with respect to wind loads, quality of mirrors, control and mounting imprecisions (Marcotte and Manning, 2013), and
(ii) developing non imaging concentrators with the aim of bringing the concentration ratio relative to the maximum as close to 1 as possible based on the fact that relaxing the imaging requirement has the potential of improving concentration performance (Winston et al., 2005).

In that regard, authors have proposed two new symmetric non imaging Parametric Trough Collectors (PmTC), one with planar absorbers (Nunez-Bootello et al., 2016a,b) and the other with circular absorbers (Nunez-Bootello et al., 2016a,b), both with 100% interception factor for rays impinging on the primary reflector within the design acceptance angle (see Fig. 1). From an optical point of view, the analysis of the characteristics of these optics and its merits through comparisons with conventional PT optics showed room for improvement (a quantitative comparison with LS2 and LS3 PTC optics can be seen in Table 1). From a structural point of view, both designs aimed at adding additional design flexibility for wind load reduction and large rim angles to control the separation between the absorber and the reflector, contributing toward a more competitive technology both in terms of cost and performance.

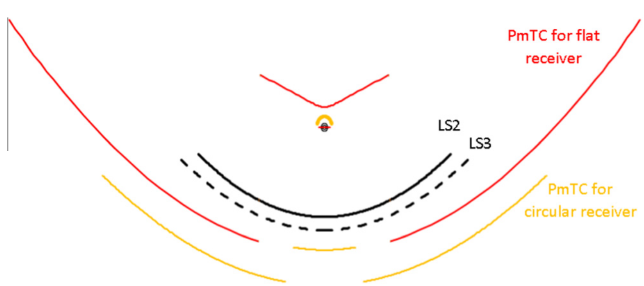

Fig. 1. LS2 and LS3 parabolic geometries compared to PmTC with circular and flat receivers.

In terms of wind loads calculation, the limited availability of full-scale wind load data for the design of unconventional geometries in renewable energy technologies makes Computational Fluid Dynamics (CFD) an appropriate tool for determining wind load distributions over solar collectors.

Despite its potential, only a small number of CFD investigations of PTCs can be found in the literature. Naeeni and Yaghoubi (2007) performed a 2D steady-state analysis using an RNG-based k-ε Reynolds-averaged Navier-Stokes (RANS) turbulence model by means of finite volumes. Zemler et al. (2013), also performed 2D steady-state analyses with an SST-RANS model and constant inlet velocity using ANSYS CFX. A 3D large-eddy simulation (LES) of a parabolic trough solar collector using a periodic boundary condition in the spanwise direction, a slip-condition for the ground and constant inlet conditions was presented by Hachicha et al. (2013) using the finite element method (FEM). Paetzold et al. (2014) performed a 3D RANS model of a PTC with a steady, uniform incoming flow using ANSYS CFX.

In contrast to CFD based on the Finite Volume Method and on Finite Element Method, here, we use a different CFD approach based on the Lattice Boltzman Method (LBM) (Chen and Doolon, 1998). This is a particle-based method where particles are constrained to move according to a finite, discrete set of velocities in an octree lattice. Smaller, unresolved turbulence scales are modeled using Large Eddy Simulation (LES), and the boundary layer physics is modeled by means of generalized wall functions (Shih et al., 1999).

Unsteady inlet boundary conditions were first used with LES in Mier-Torrecilla et al. (2014) to estimate both mean and root-mean-square (RMS) wind loads of a 3D PTC model. Andre et al. (2014, 2015) compared the 3D LES results for the lattice Boltzmann and finite element methods with experimental data. Results of these works show:

(i) that LBM results are comparable to experimental data and Finite Element results with good agreement if the same boundary conditions are appropriately reproduced (Andre et al., 2015),
(ii) that the relative mean differences of the numerical results with respect to experimental data are within 10%, being therefore of the same order as experimental uncertainty (Mier-Torrecilla et al., 2014),

Table 1
Optical comparison between LS2, LS3, PmTC with flat receiver and PmTC with circular receiver.

	LS2	LS3/Eurotrough	PmTC with flat absorber	PmTC with circular absorber
Absorber perimeter (m)	0.22	0.22	0.22	0.22
Half acceptance angle (°)	0.790	0.688	0.751	0.802
Aperture width (net) (m)	5.00	5.76	9.95	8.12
Geometric concentration (net) C	22.7	26.2	45.2	36.93
Maximum concentration Cmax	72.5	83.3	76.3	71.4
C/Cmax ratio	0.31	0.31	0.59	0.52
Etendue of the captured radiation	0.138	0.138	0.261	0.227
Maximum etendue the receiver can accept	0.440	0.440	0.440	0.440
Number of reflections	1	1	2	1.15